ARMY RESEARCH LABORATORY

DEA-G-1060 German/U.S. Workshop on Electrothermal-Chemical Gun Propulsion

by William Oberle
EDITOR

ARL-SR-75

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Army Research Laboratory
Aberdeen Proving Ground, MD 21005-5066

ARL-SR-75 **August 1998**

DEA-G-1060 German/U.S. Workshop on Electrothermal-Chemical Gun Propulsion

William Oberle, Editor
Weapons and Materials Research Directorate, ARL

Abstract

A German-U.S. workshop, under the auspices of DEA-G-1060, focusing on electrothermal-chemical (ETC) gun propulsion was held at the U.S. Army Research Laboratory, Weapons and Materials Research Directorate, Aberdeen Proving Ground, MD, on 27–28 January 1998. The workshop was attended by approximately 60 researchers from Germany and the United States. Eighteen invited talks covering the areas of ETC Program Overviews, Pulsed Power, Modeling and Simulation, ETC Systems, and Plasma Propellant Interaction were presented during the two days.

Acknowledgments

The author would like to thank all those who participated in the DEA-G-1060 German/U.S. workshop on electrothermal-chemical gun propulsion. Special thanks goes to Suzette Shields, Gary Katulka, and Gloria Wren for their extra efforts and assistance in organizing the workshop.

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1. Introduction

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A German-U.S. workshop, under the auspices of DEA-G-1060, focusing on electrothermal-chemical (ETC) gun propulsion was held at the U.S. Army Research Laboratory, Weapons and Materials Research Directorate, Aberdeen Proving Ground, MD, on 27–28 January 1998. The workshop was attended by approximately 60 researchers from Germany and the United States. Eighteen invited talks covering the areas of ETC Program Overviews, Pulsed Power, Modeling and Simulation, ETC Systems, and Plasma Propellant Interaction were presented during the two days.

The workshop agenda is provided in section 2, and a list of the participants is given in section 3. For the majority of the presentations, copies of the slides can be found in section 4.

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2. Agenda

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DEA-G-1060
German/U.S. Workshop
on
Electrothermal-Chemical Gun Propulsion

27–28 January 1998

Aberdeen Proving Ground, MD

Tuesday, 27 January 1998

0900	Administrative Remarks	W. Oberle
0905	Opening Remarks - DEA-G-1060	T. Minor
0915	Welcome & WMRD Overview	I. May

German & U.S. Program Overview

0930	German ETC Program - Goals, Schedule, and Rationale	H. Maag
1000	U.S. ETC Program - Goals, Schedule, and Rationale	W. Oberle
1020	BREAK	

ETC Pulse Power

1040	Status of Pulse Power Development - Germany	T. Weise
1110	Status of Pulse Power Development - United States	I. McNab
1140	LUNCH	
1300	Magnet Motors Activities in Pulse Power & Storage	M. Heeg
1330	High-Temperature Materials Research With Metalized-SiC for Pulsed Power Electric Guns	G. Katulka

ETC Modeling

1400	German Modeling & Simulation Efforts	W. Romhild
1430	U.S. Modeling & Simulation Efforts	G. Wren
1500	BREAK	

System Perspective

1520	Advanced Armament System Development & Weaponization	R. Staiert
1550	Modeling Weapons Effects on Mobility	S. Fish
1610	Adjourn	
1830	No Host Dinner	

Wednesday, 28 January 1998

Plasma Propellant Interaction

0900	Plasma-Propellant Diagnostics Under the Army/DSWA ETC Program	L. Thornhill
0930	Basic Research in the Chemistry of Plasma/Propellant Interaction	R. Pesce-Rodriguez
1000	ETC Closed Chamber Experiments - TZN	H. Haak
1030	BREAK	
1050	ETC Closed Chamber Experiments	M. Del Guercio
1120	Closed Chamber Experiments & ETC Efforts at ISL	D. Hensel
1150	LUNCH	
1300	Plasma Radiative & Convective Interaction With Propellant Beds	K. White
1330	Large-Caliber ETC Gun Firings - Germany	T. Weise
1400	EEF Follow-on Program - A Demonstration of Precision Ignition and Temperature Compensation in 120-mm ETC Test Firings	J. Dyvik
1430	Closing Remarks	
1445	Adjourn	
1500	Government - Government Meeting	

Attendee List

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Name	Organization	Phone	Fax	E-mail
William R. Anderson	WMRD-ARL	410-278-9992	410-278-7333	willie@arl.mil
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Presentations

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Overview of the German ETC Activities within the Scope of NGP

ETC Workshop on ETC Technology
at ARL Aberdeen PG, MD from 27. to 28.01.1998

Hans-Jürgen Maag, BWB WF IV 6/ Dr. Hans Knöchel WTD 91 Dez 210

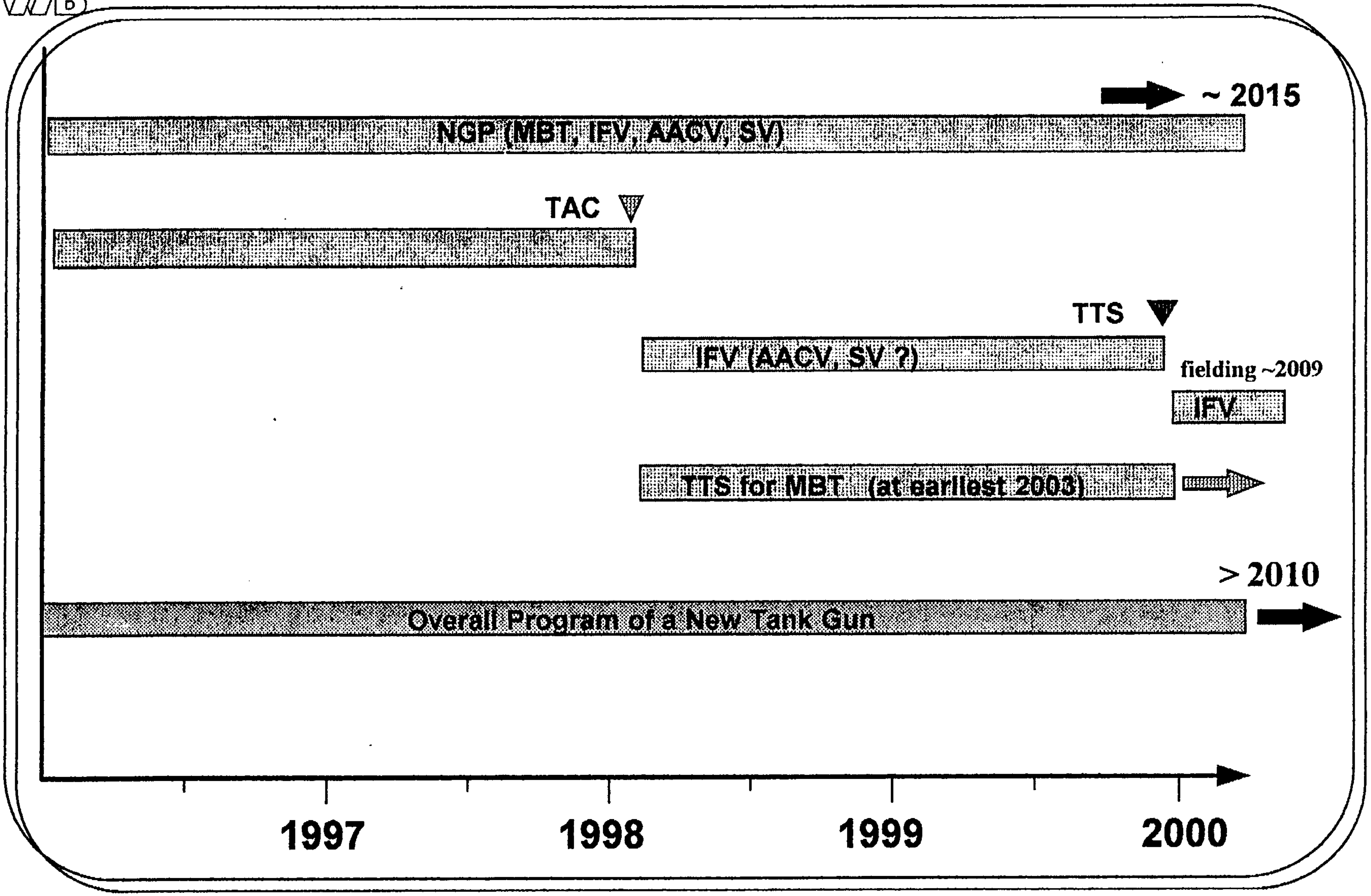
Overview of the German ETC Activities

Outline

- Time Schedule of NGP Studies
- Objectives of the Current German ETC Efforts
- Status of Current Tasks
- Summary

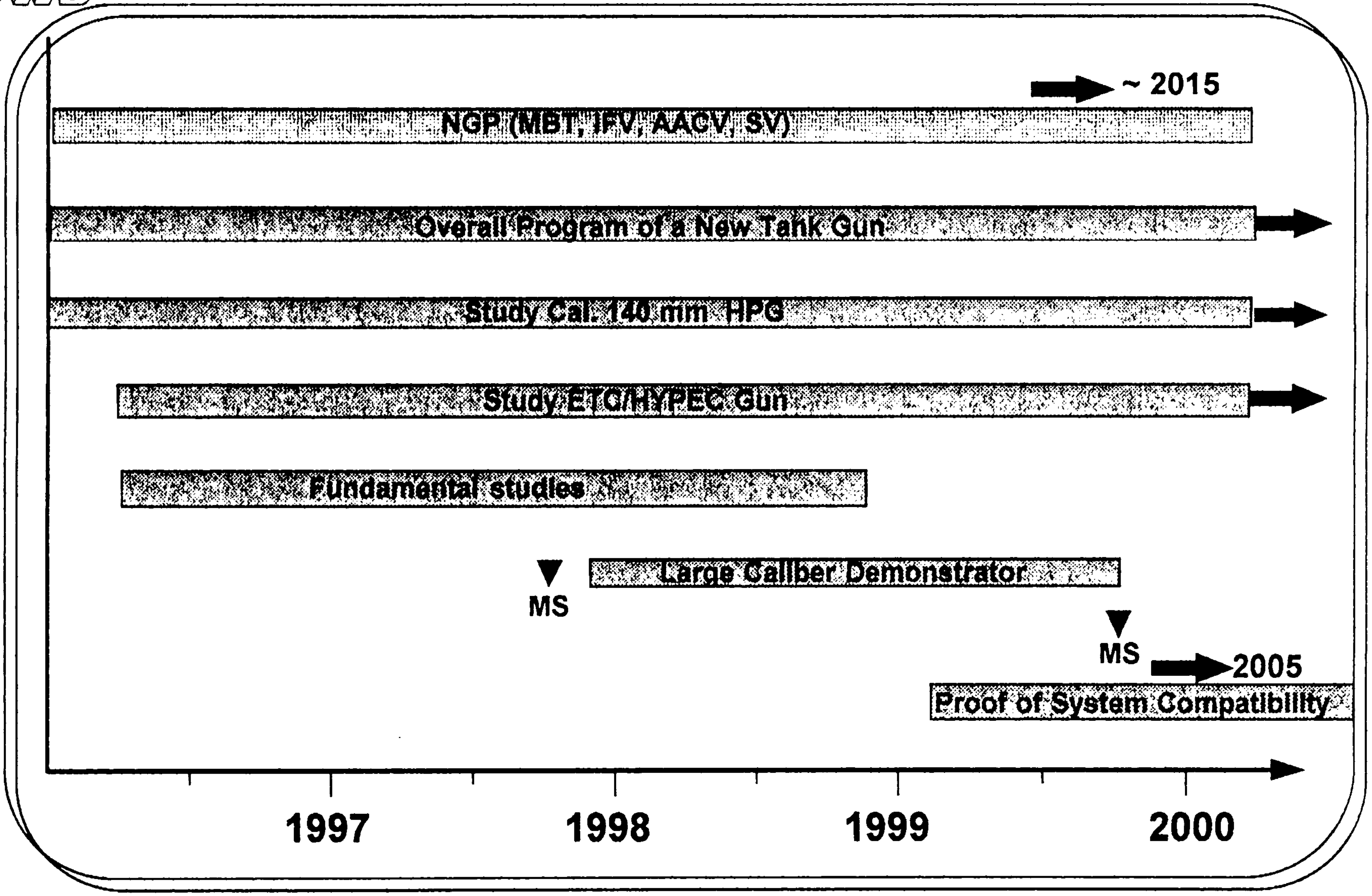
Overview of the German ETC Activities

WF IV 6



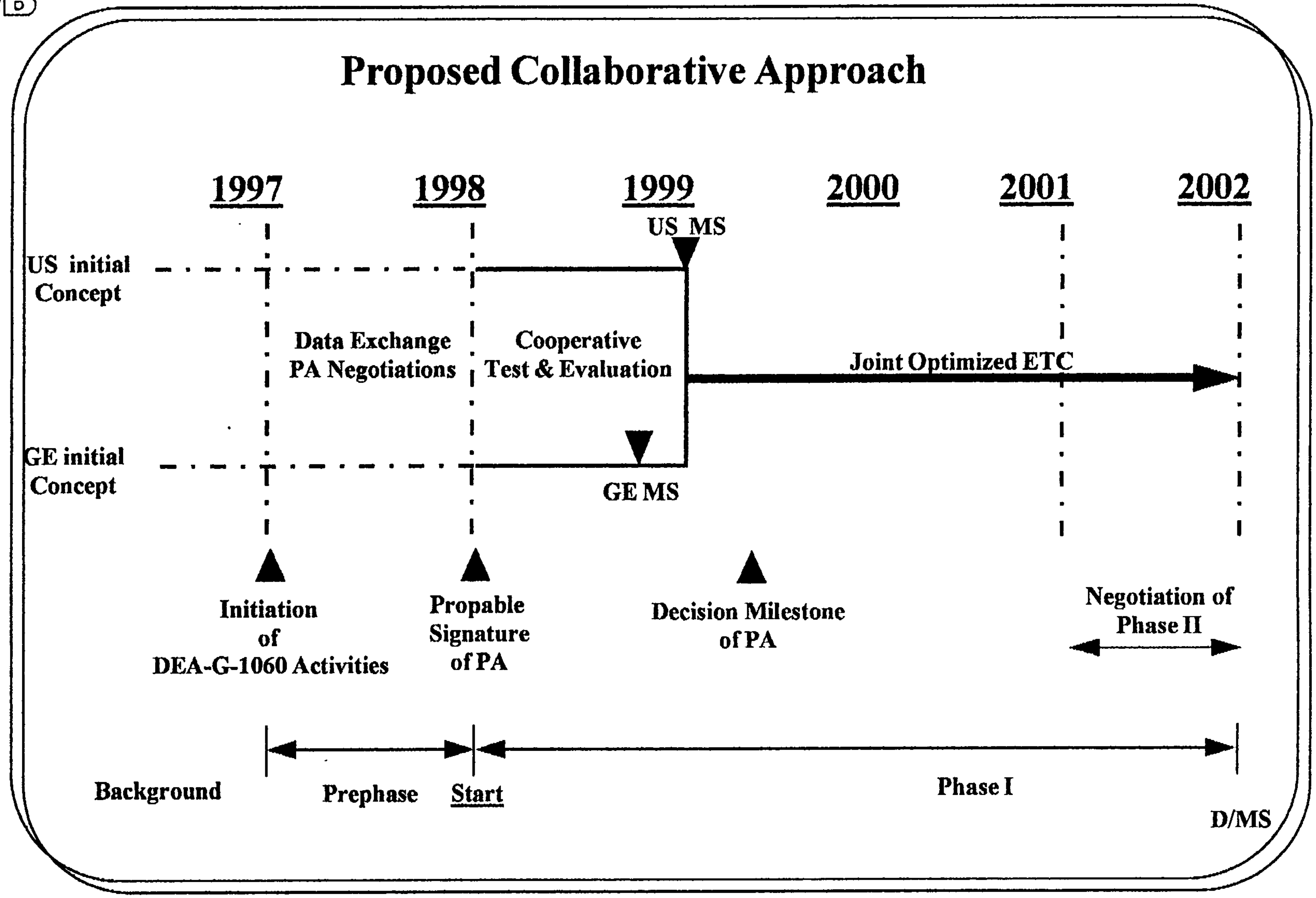
Overview of the German ETC Activities

WF IV 6



Overview of the German ETC Activities

WF IV 6



Overview of the German ETC Activities

WF IV 6

Main Objectives:

Design and development of a 120 mm cal ETC Gun suitable to meet the lethality requirements of an 140 mm cal Tank Gun which is compliant with the requirements for integration into Future Military Vehicle Systems

Overview of the German ETC Activities

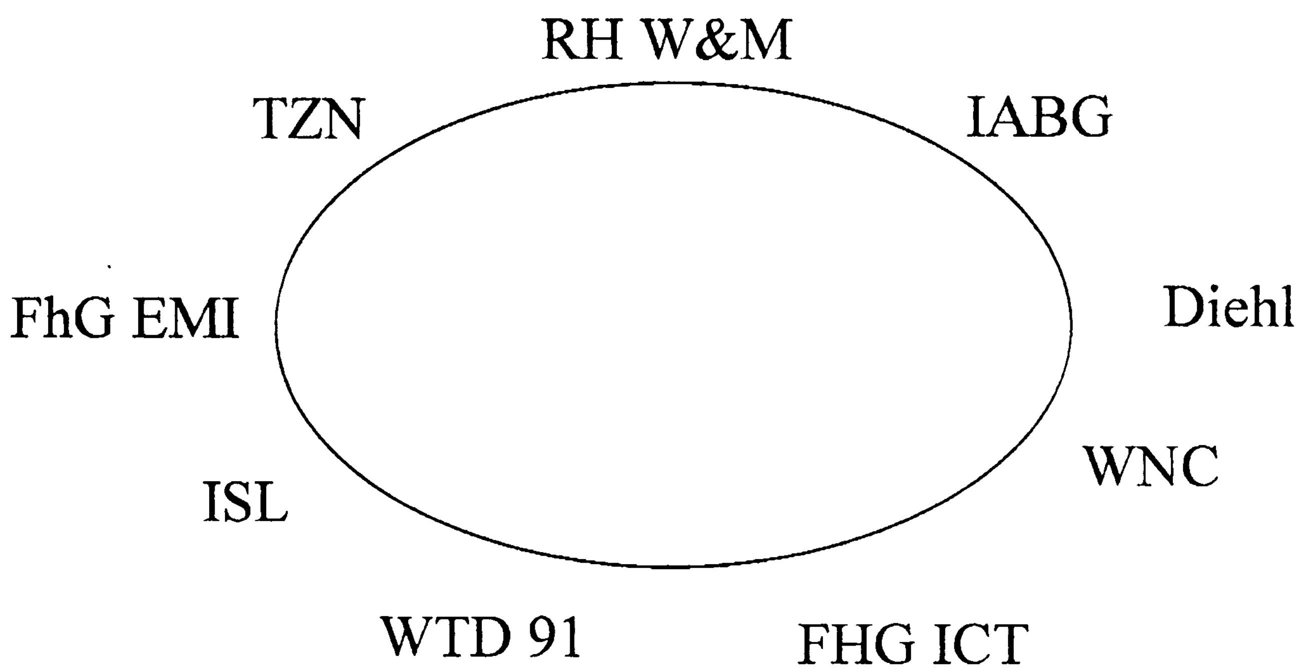
Tasks/Efforts to meet the ETC-Gun Requirements

- Design and pre-selection of suitable ETC-Concepts
- Fundamental studies to understand the physical and chemical phenomena occurring during interaction of plasma and propellant
- Based on the results of the above mentioned investigations the following tasks will be carried out:
  - o Evaluation and review of the pre-selected concepts
  - o Design and manufacture of new propellants suitable for plasma ignition
  - o Definition and adjustment of plasma criteria (e.g. field of radiation, absorption coefficient of particles in the gas phase and of the solid propellant) to achieve an optimal energy/heat transfer into the propellant.

Overview of the German ETC Activities

WF IV 6

German ETC Working Group



Overview of the German ETC Activities

WF IV 6

Tasks of the Working Group

- Complementary work to allow use of existing know-how and equipment
- Critical assessment of the results of each institution and company involved
- Continous data exchange
- Identification of synergetic effects
- Preparation of an interaction task list for mutual support

Overview of the German ETC Activities

WF IV 6

Schedule of Interactions

Nr.	Vorgangsname	95	1996	1997	1998	1999	2000	2001
1	**1 Studie ETC/HYPEC Phase II**							
2	**1.1 Zuarbeiten TZN**							
3	1.1.1 Arbeiten für Konzeptverbesserungen							
4	1.1.2 Leistungsnachweis ETC/HYPEC						30.11.	
5	**1.1.3 ETC/HYPEC Daten an IABG/IC/ISL**							
6	1.1.3.1 Konzeptdaten :Ladungsaufb usw.							
7	1.1.3.2 Versuchsergebnisse: U, I, WEB usw.,							
8	**1.2 Zuarbeiten IABG**							
9	**1.2.1 Simulation ETC/ HYPEC**							
10	1.2.1.1 Rechnungen mit Paramtervar.							
11	1.2.1.2 Anpassung der Codes							
12	**1.2.2 Versuchsbegleitung /Simulations ETC**							
13	1.2.2.1 Erweiterungen Abbrandgesetz							
14	1.2.2.2 Rechnungen mit Plasmabr.TZN							
15	1.2.3 Simulation der EMI Versuche							
16	1.2.4 Vergleich der EMI Konzepte							
17	1.2.5 Simulationserg. TZN/EMI an ICT							
18	1.2.6 Daten zur Strahlungsemission an ICT							
19	**1.3 Zuarbeiten ICT**							

Overview of the German ETC Activities

Tasks of WTD 91 Dez 210

- Official representative responsible in the field of propellant design and interior ballistics
- Definition of specifications and requirements for new propellants (conventional and for ETC applications)
- Assignment of studies to the companies and institutions to find new propellants for conventional and ETC applications
- Evaluation of the results of the current ETC studies concerning power potential of new propellants and feasibility of selected ETC concepts
- Support of the experiments and test firings of the BWB contractors and government funded institutions, regarding calculations and implementation of WTD 91 equipment used to record projectile velocity, pressure curves etc.

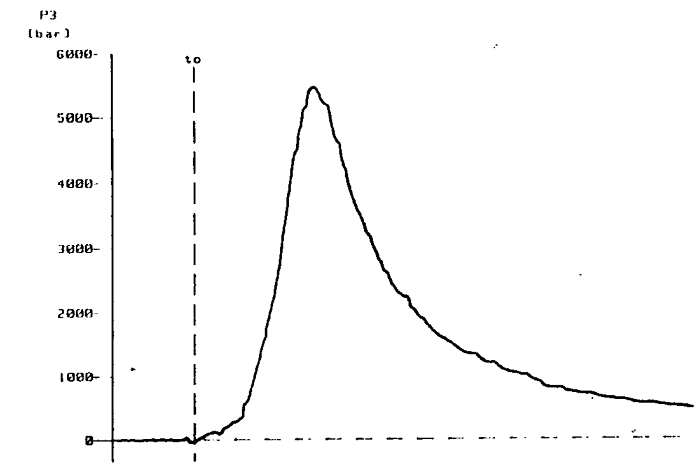
Overview of the German ETC Activities

WF IV 6

Tasks of Diehl

- Closed vessel test for pre-selection of suitable ETC propellants manufactured and supplied by FhG ICT and ISL
- ETC test firings with medium caliber guns (30 to 80 mm) varying pulse length, electrical energy input and loading density
- ETC test firings using propellants with different properties e.g. coating, consistence, chemical composition, energy impetus, grain size etc.
- Investigations to integrate a plasma igniter into a less than cal 30 mm cartridge and to carry out ignition tests with and without propellant

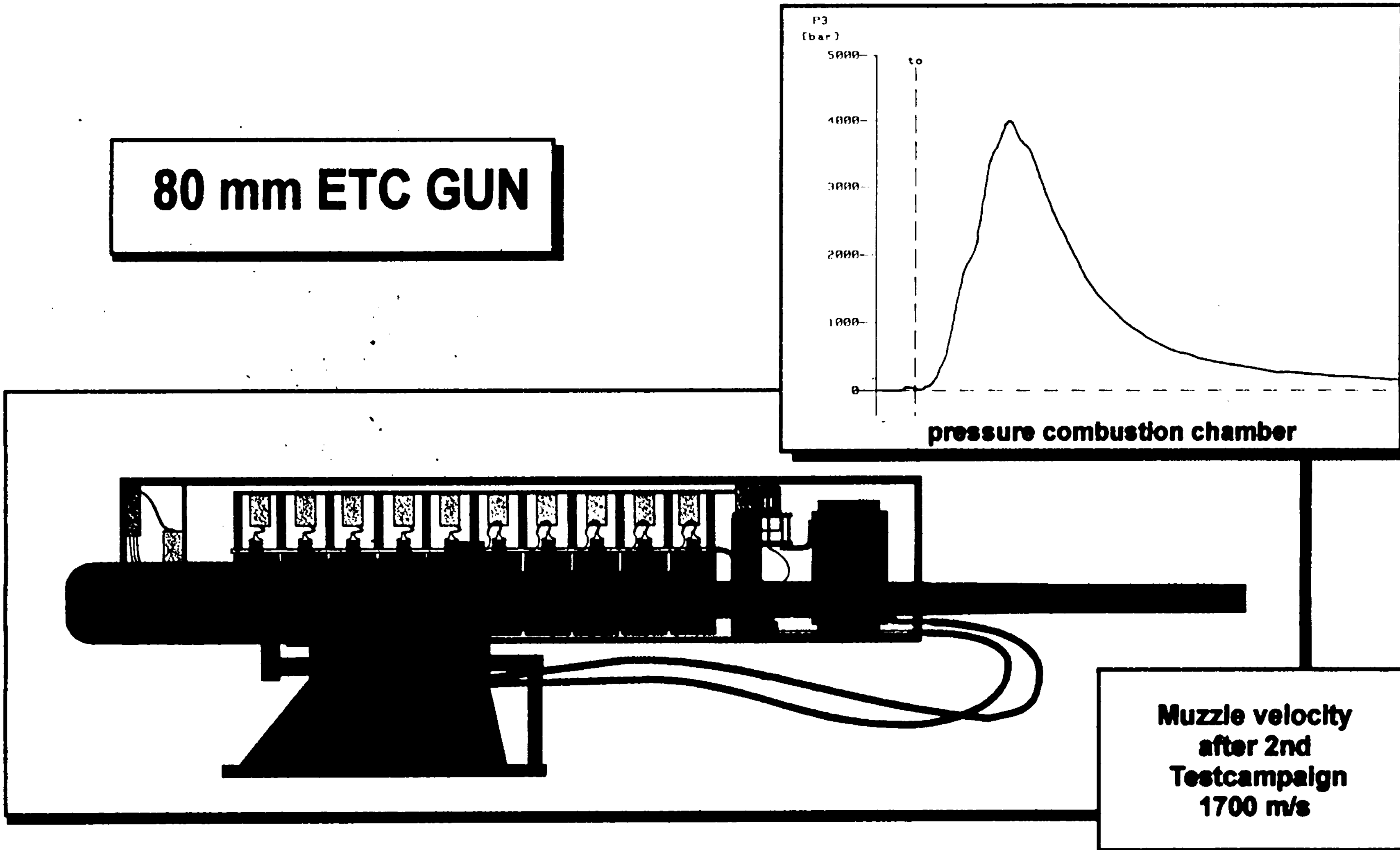
30 mm ETC GUN



pressure combustion chamber

**Muzzle velocity
Round No. 282
2400 m/s**

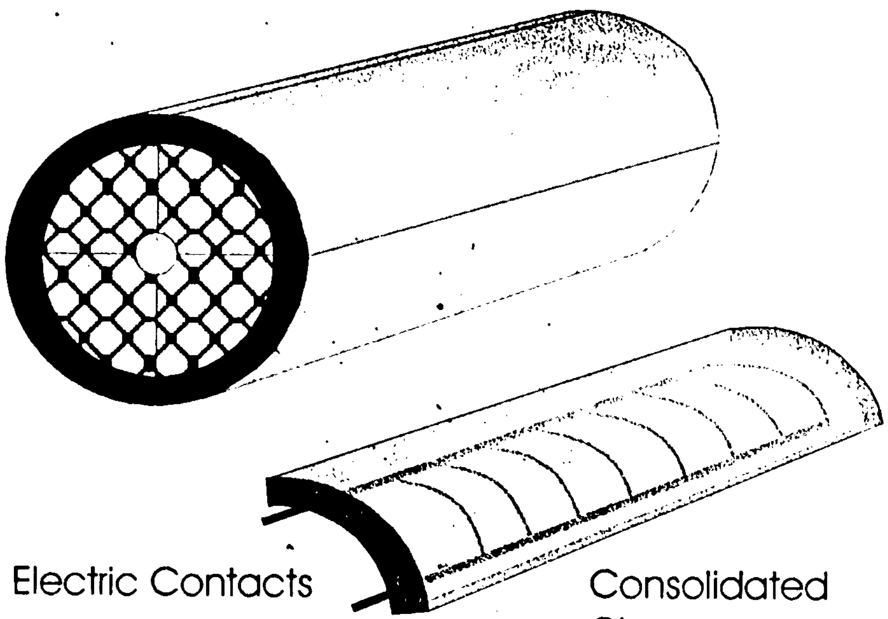
80 mm ETC GUN


P3
[bar]
5000
4000
3000
2000
1000
0
to
pressure combustion chamber
Muzzle velocity
after 2nd
Testcampaign
1700 m/s

Overview of the German ETC Activities

Tasks of FhG EMI

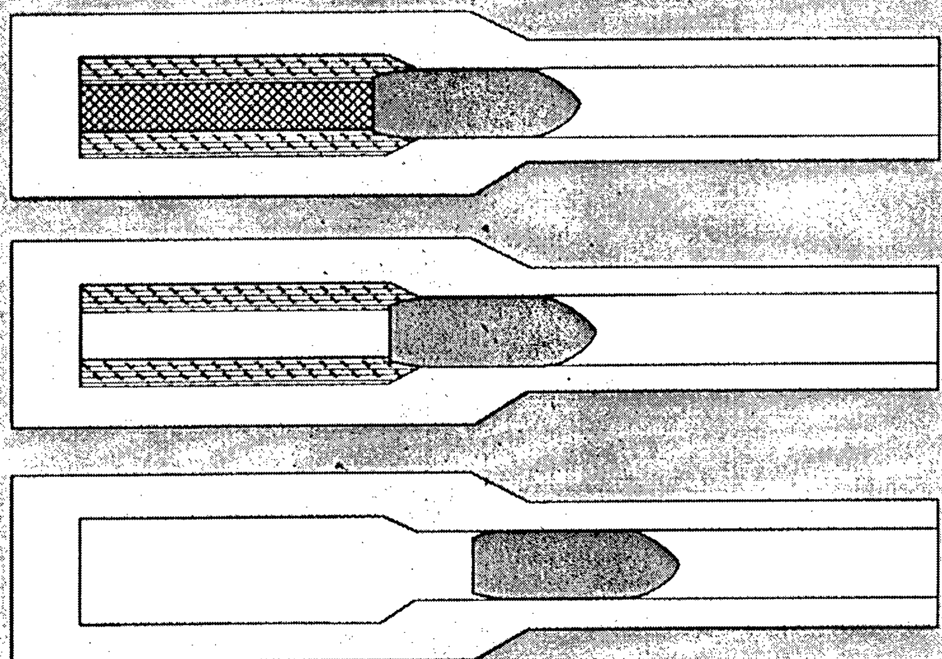
- Design and manufacture of new charge configurations using different charge densities and propellants
- Design and manufacture of igniter systems suitable to control combustion behavior
- Design and manufacture of test devices (e.g. x-ray diagnostics, closed vessels, medium cal. guns to prove the feasibility of new charge configurations and igniter concepts



Requirements for the Consolidated Charge:

- Pressure Resistant
- Defined Local Position
- For Short Time Temperature Resistant

Principle of a Gun Propellant Charge with Two Different Propellant Types, Sequential Ignition



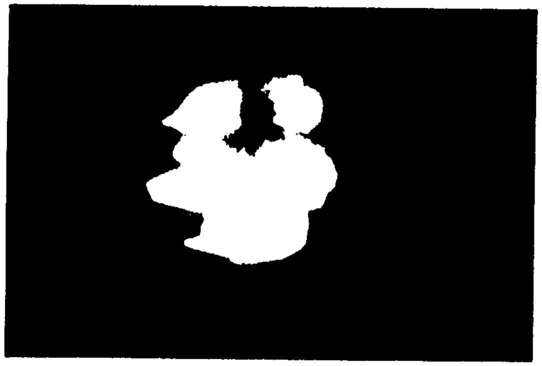
Center Charge:
Granular Propellant

Outer Charge:
Consolidated Propellant

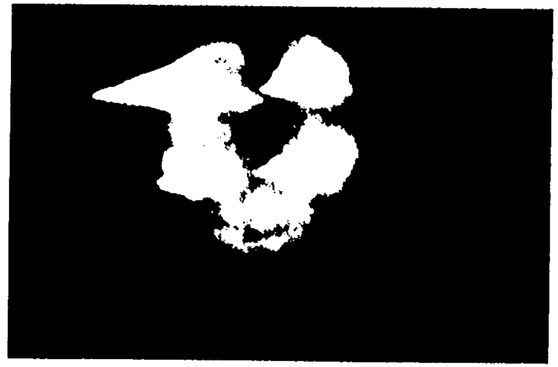
Fraunhofer Institut Kurzzeitdynamik Ernst-Mach-Institut EMI

BWB — WF IV 6

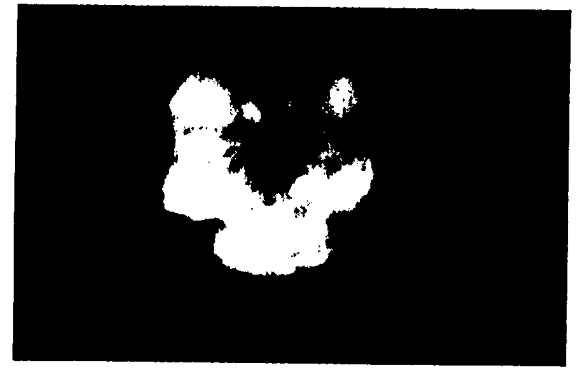
Combustion of a Consolidated Charge Ignited by an Electric Arc



70 μs

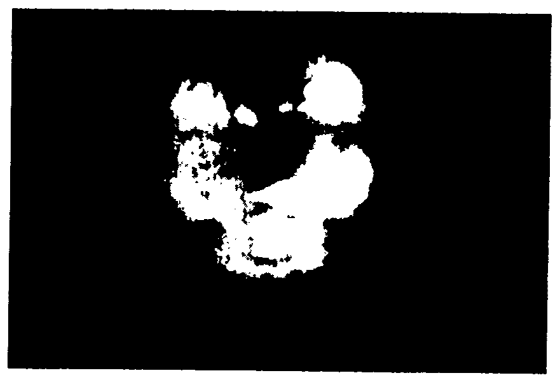


110 μs

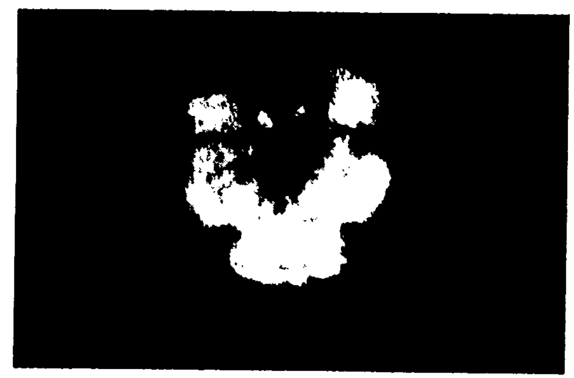


135 μs

90 μs



130 μs



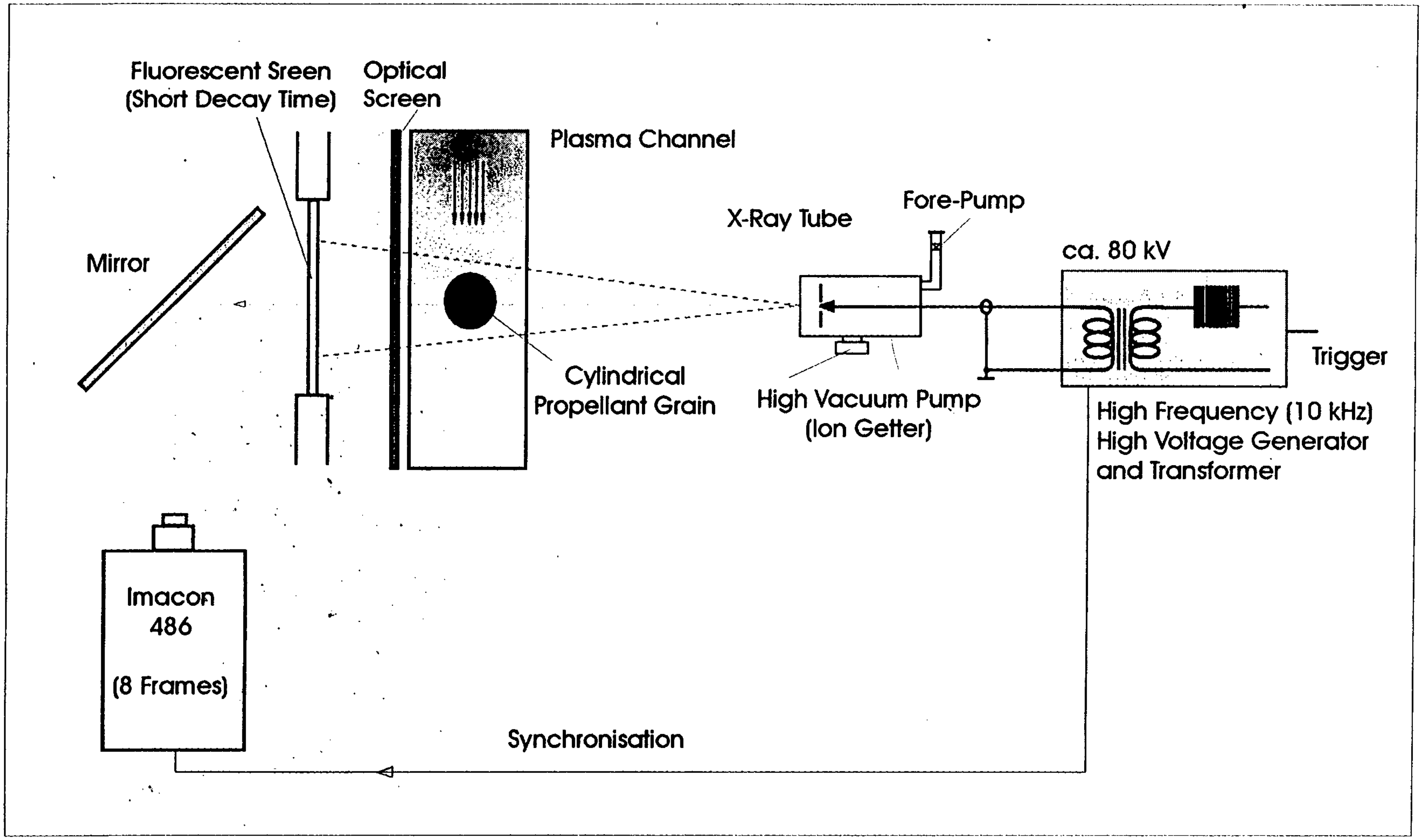
140 μs

Fraunhofer Institut Kurzzeitdynamik Ernst-Mach-Institut

EMI

BWB — WF IV 6

Set-Up for Measuring the Erosive Burning of a Propellant Grain in a Plasma Jet



Overview of the German ETC Activities

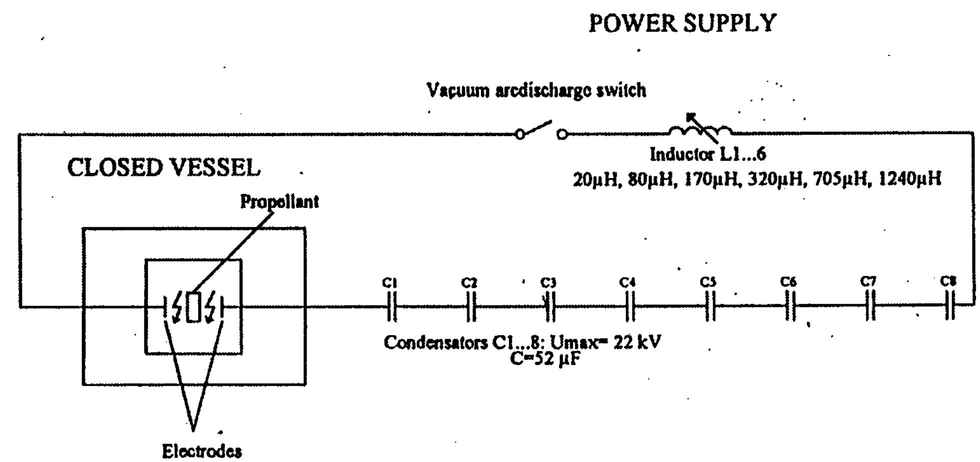
WF IV 6

Tasks of FhG ICT

- Identification of additives suitable to produce hydrogen to reduce the molecular mass of the combustion gases and requiring only low electric energy input for this process
- Design and manufacture of test devices to investigate the interactions between plasma and propellant
- Design and manufacture of new propellants suitable to achieve a very efficient heat transfer from plasma into the propellant, based on the above mentioned investigations
- Investigations and calculations to find new combustion laws suitable to describe the burning behavior influenced by the plasma ignition
- Extension of the ICT Code for low temperature plasma

BWB WF

Experimental equipment for ETC-technology

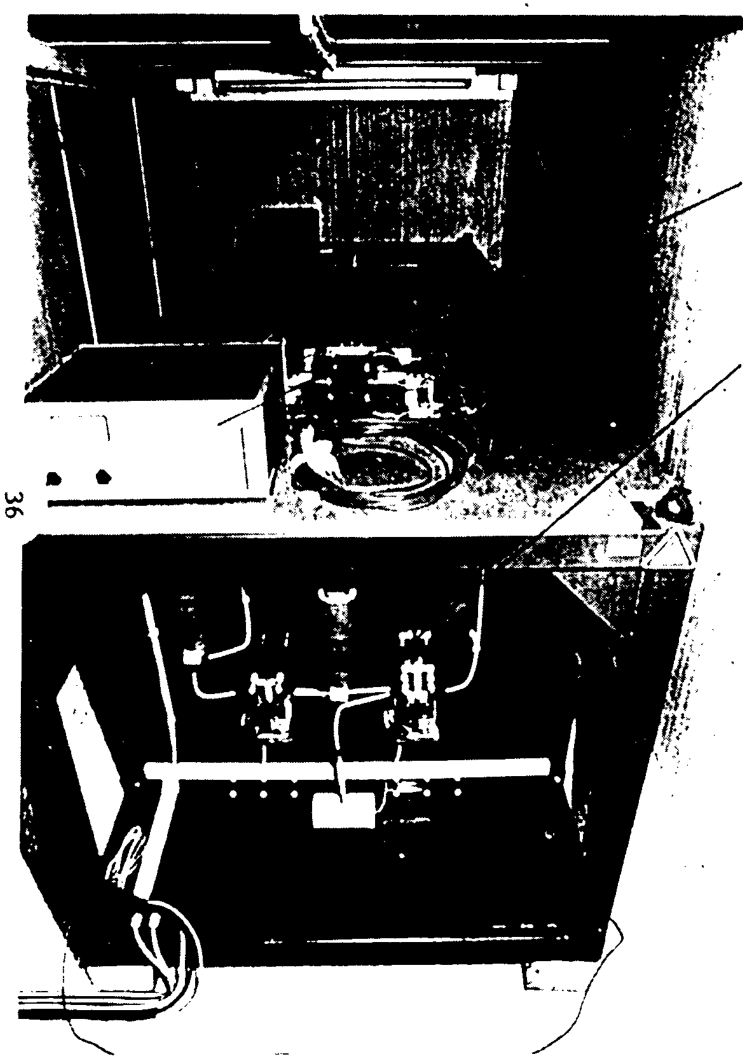


Technical data of Closed Vessel: Volume= 100 ml
P max = 400 Mpa
two saphire windows

Technical data of Power Supply: max. storage energy = 100 kJ
max. current peak = 100 kA
max. voltage = 22 kV

Measurement: pressure, temperature, radiation

Power Supply



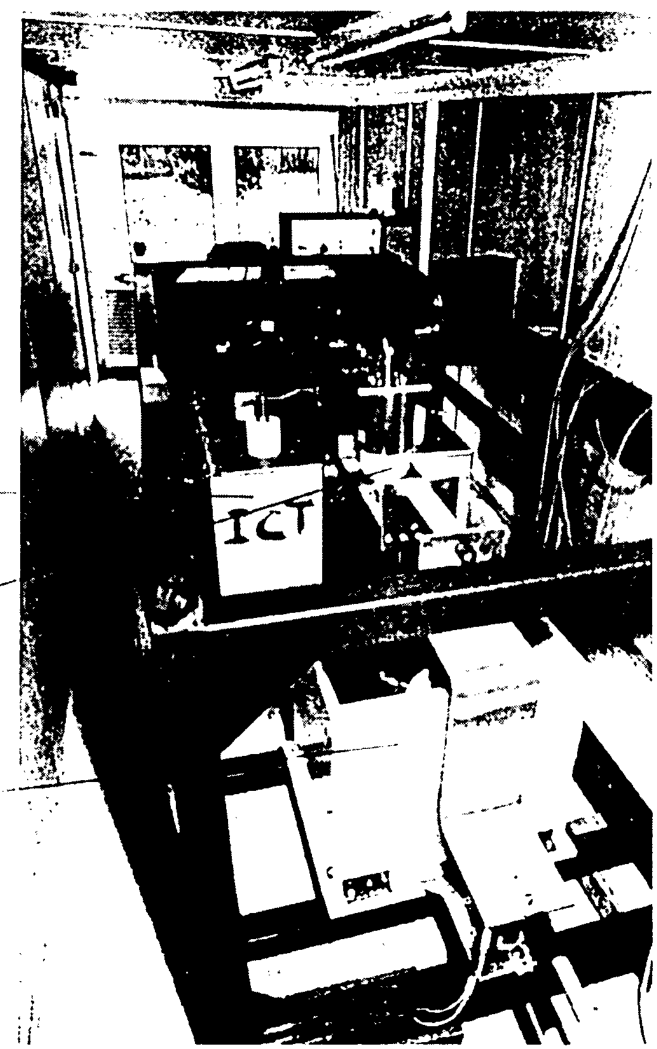
Charge Station

Charge/Dump Panel

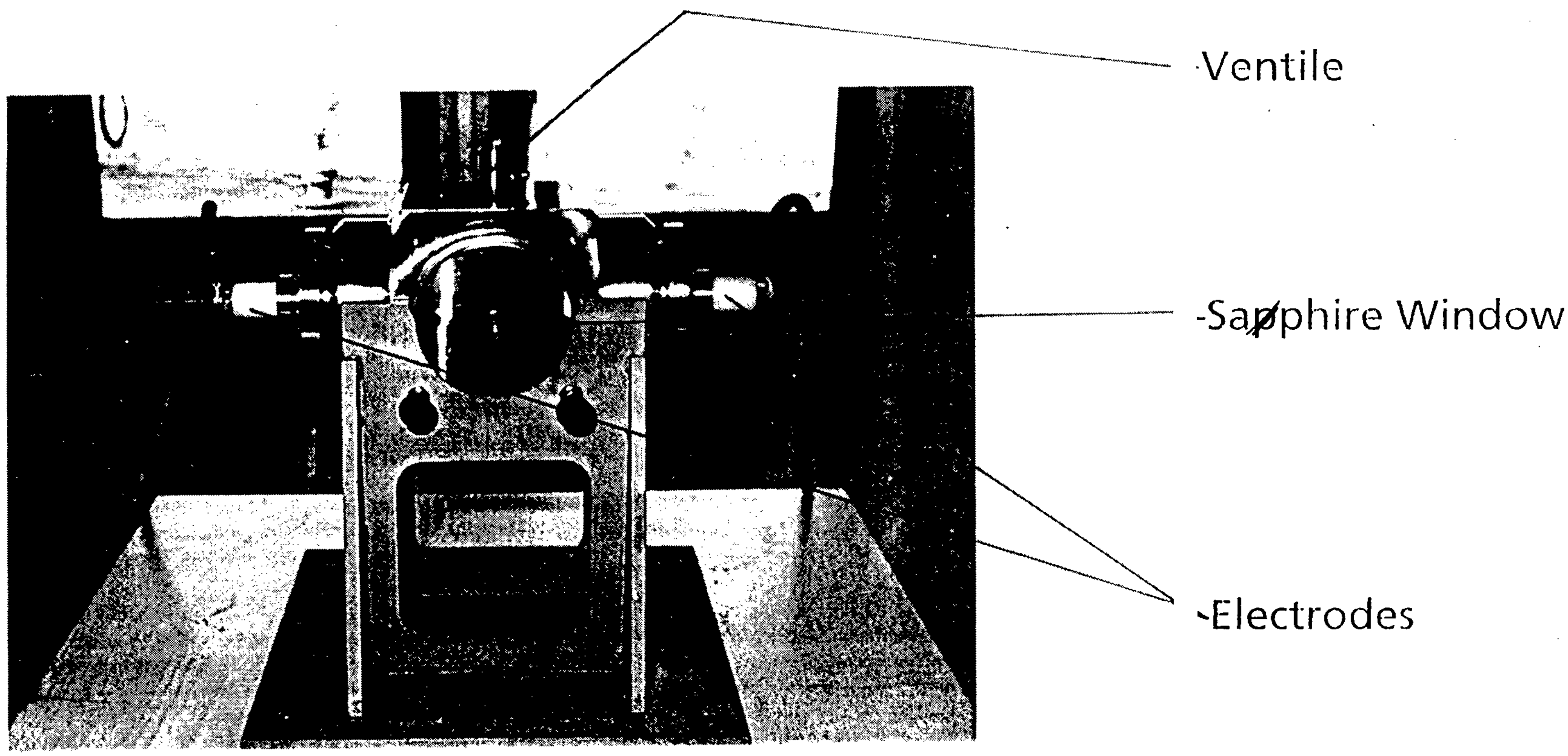
Condensators (8)

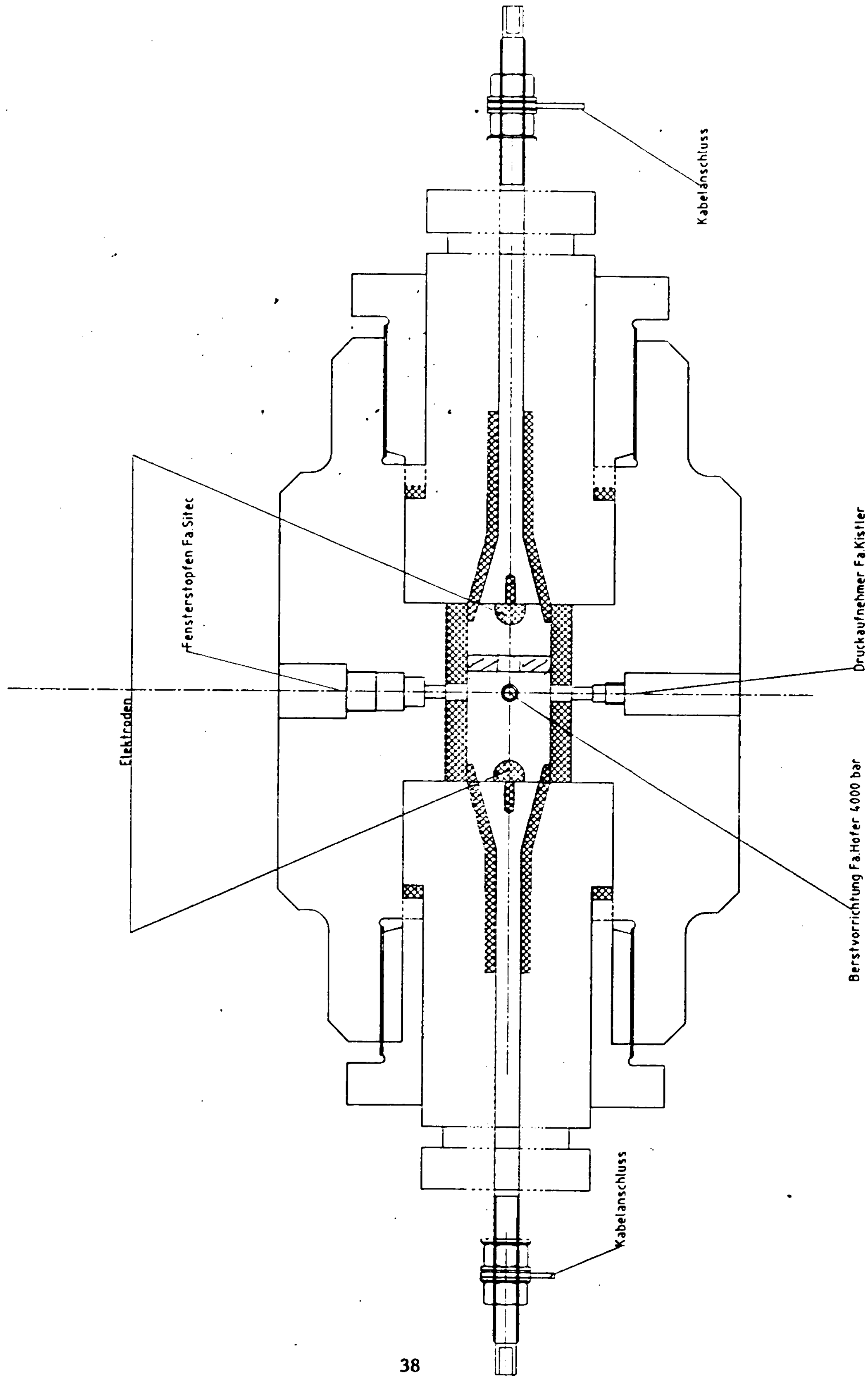
Switch

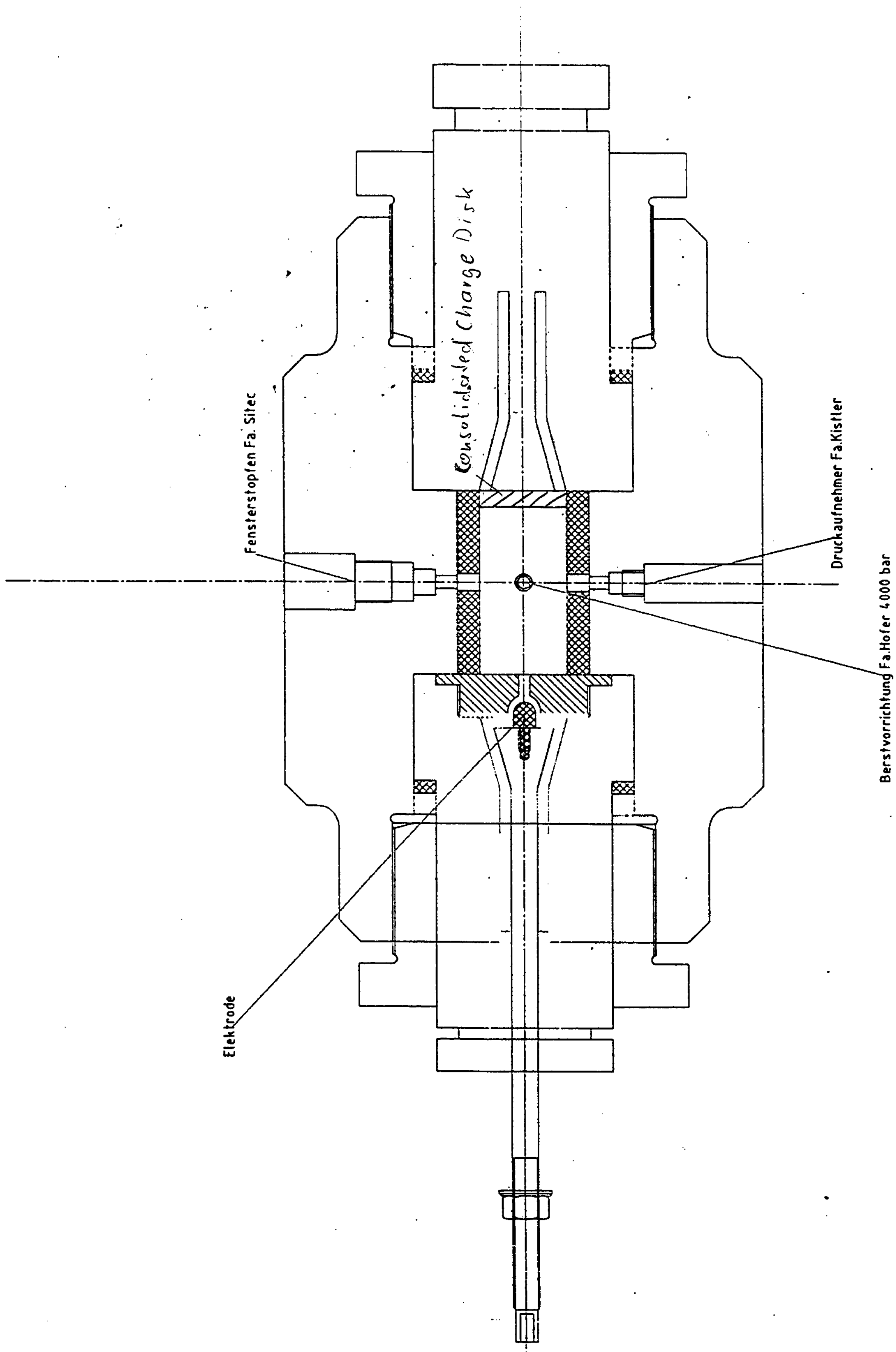
Inductor



Closed Vessel




Kabelanschluss
Fensterstopfen Fa. Sitec
Druckaufnehmer Fa. Kistler
Elektroden
Berstvorrichtung Fa. Hofer 4000 bar
Kabelanschluss


Fensterstopfen Fa. Sitec
Consolidated Charge Disk
Druckaufnehmer Fa.Kistler
Berstvorrichtung Fa.Hofer 4000 bar
Elektrode

Overview of the German ETC Activities

Summary

- The future GE tank gun program is integrated into the overall NGP program that has been set up to develop and field a new combat vehicle family between FY2009 (IFV) and FY 2015 (MBT).
- The objective of the ETC program is to develop a 120 mm caliber ETC gun suitable to meet the lethality requirements of a 140 mm caliber tank gun compliant with the requirements for integration into the Future MBT.
- The results of our current studies showed that performance and system requirements of a future ETC tank gun can be achieved.
- Further investigations are necessary to better understand the basic processes of interaction between plasma and propellant to optimize available plasma igniters and propellants

US ETC Program
Goals, Schedule & Rationale

Presented
at
German/US Workshop
on
Electrothermal-Chemical Gun Propulsion
(DEA-G-1060)

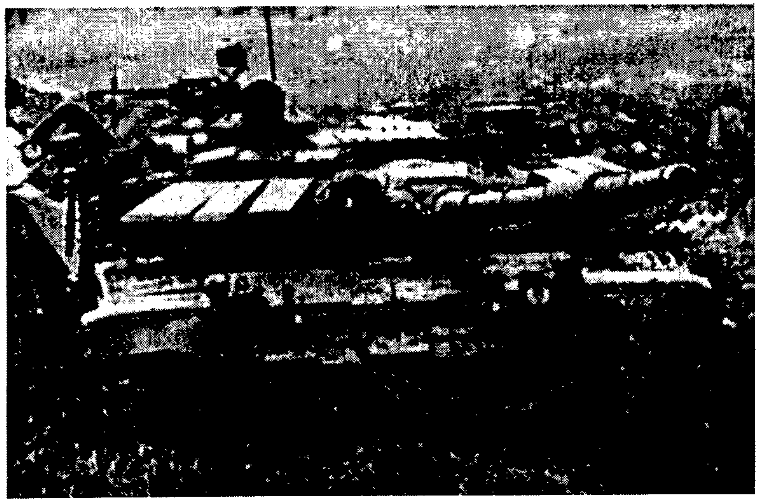
27 - 28 January 1998

William Oberle
Army Research Laboratory
Aberdeen Proving Ground, MD

Outline

- Threat/FCS/EG Program
- ETC Goals & Rationale
- Program Structure & Schedule

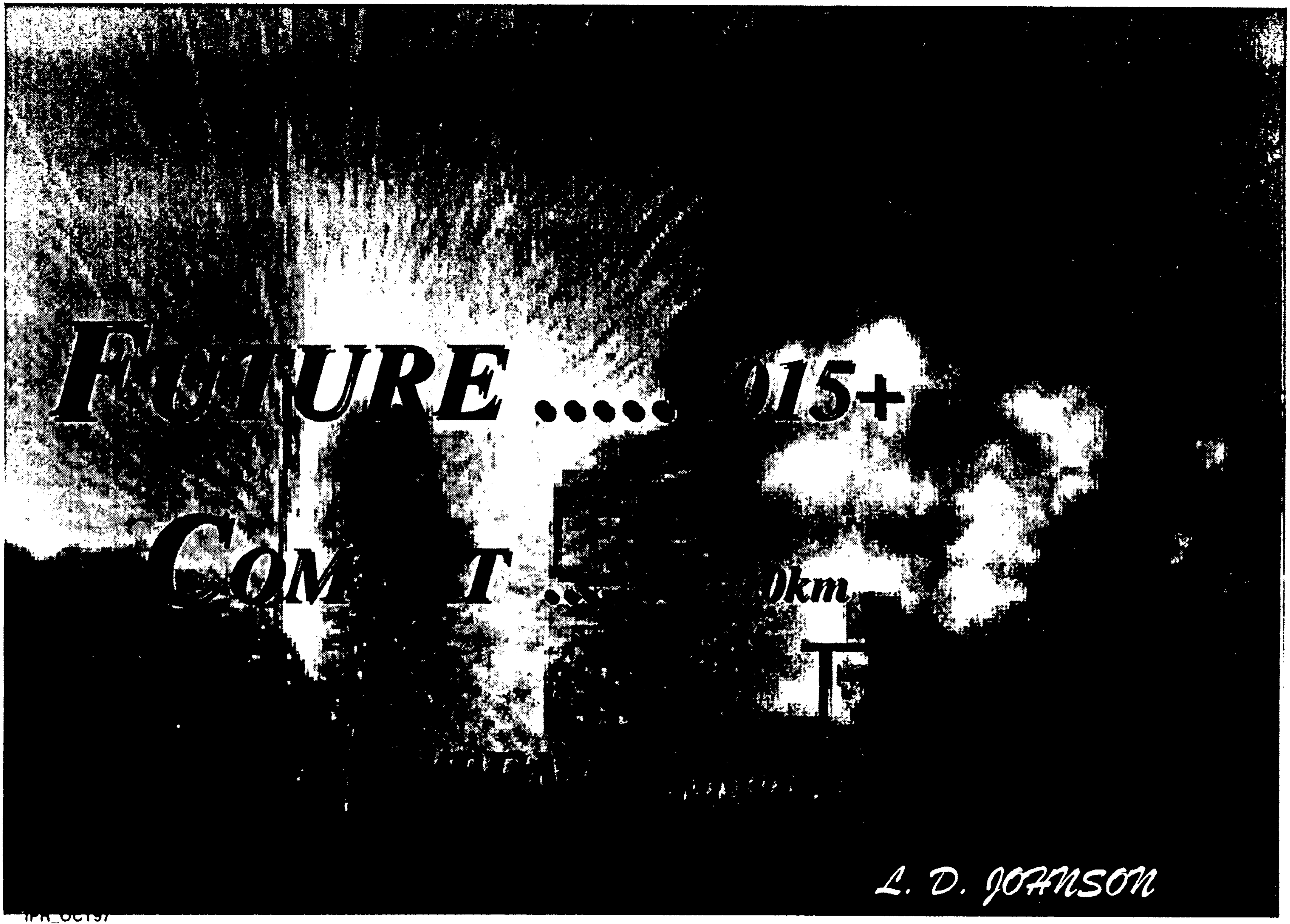
Continuing Threat Evolution



- Explosive Reactive Armor (ERA) effective against kinetic energy (KE) rounds
- Active Protection Systems (APS)

Franco–German tie-up with Russia on tank defense

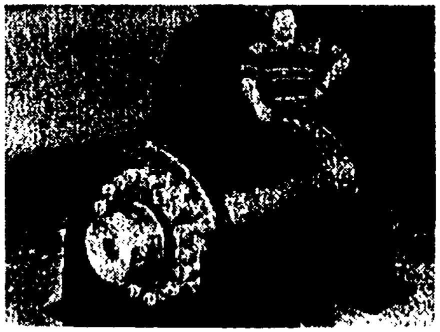
The Arena tank self-protection system, developed by KBP of Russia and seen here aboard a T-80 tank, is expected to be displayed overseas for the first time aboard a French tank at the Eurosatory exhibition in June 1996. The recently formed Franco–


FUTURE
015+
COM
T
0km
L. D. JOHNSON

FCS Main Armament Options

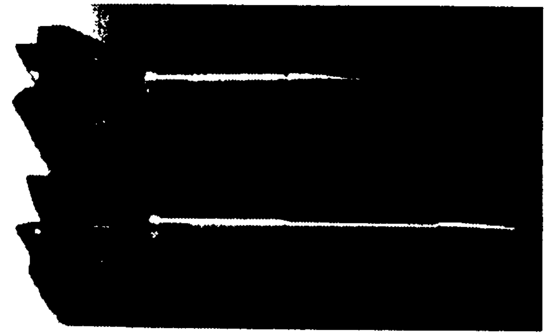
- Electromagnetic (EM) Railgun
- Electrothermal Chemical (ETC)
  - ◊ includes advanced conventional approaches
- Kinetic Energy Missiles

Pulsed Power



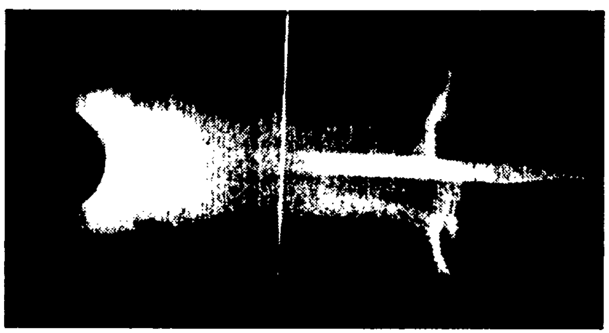
Highest Priority

Hypervelocity Utility

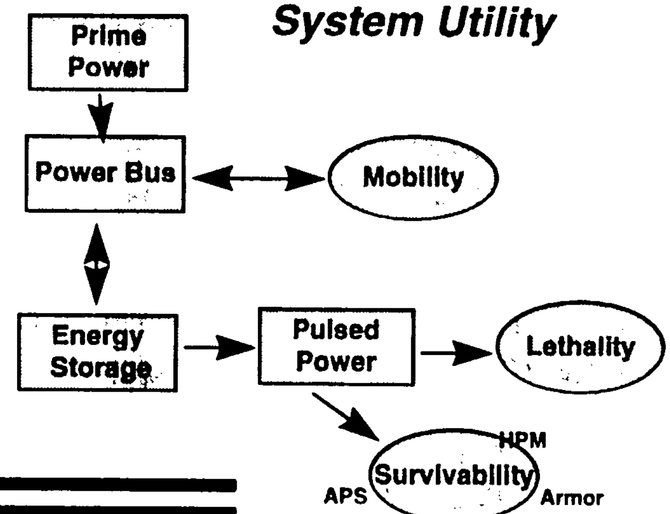


High Priority

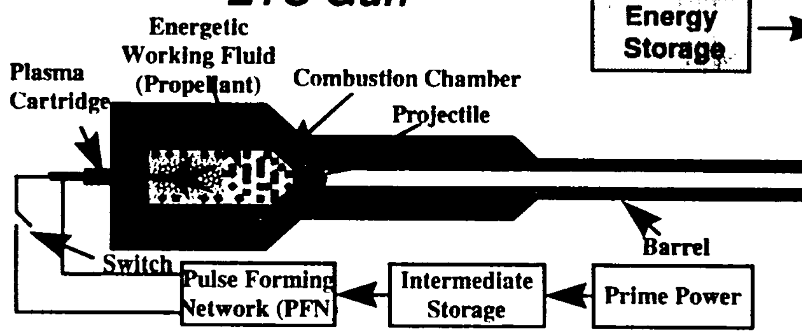
EM Launcher



System Utility



ETC Gun



IPR_OCT97

ETC Direct Fire Program Goal: Demonstrate 140mm conventional gun lethality in a 120mm ETC gun.

Approach:

- ***Understand the physics unique to the ETC process (research, laboratory & sub-scale)***
- ***Apply this understanding to develop practical concepts & hardware suitable for weapons (engineering)***
- ***Validate the concepts through full scale gun firings***

Increasing Gun Performance & Lethality

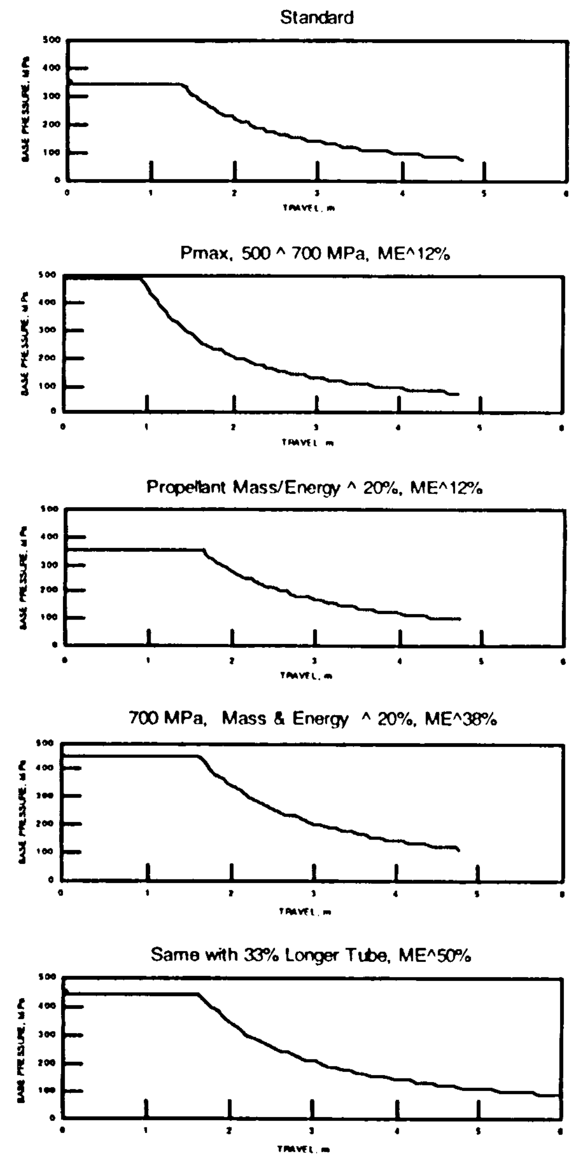
- *Increase ballistic performance (muzzle kinetic energy): Energy + Efficiency*

ETC – *reduced propelling charge temperature sensitivity to permit operation at higher pressures (eff)*
ETC – *increased propellant mass (eng)*
ETC – *increased propellant energy (eng)*
– *longer travel (eff)*

- *Increase accuracy, P_h*

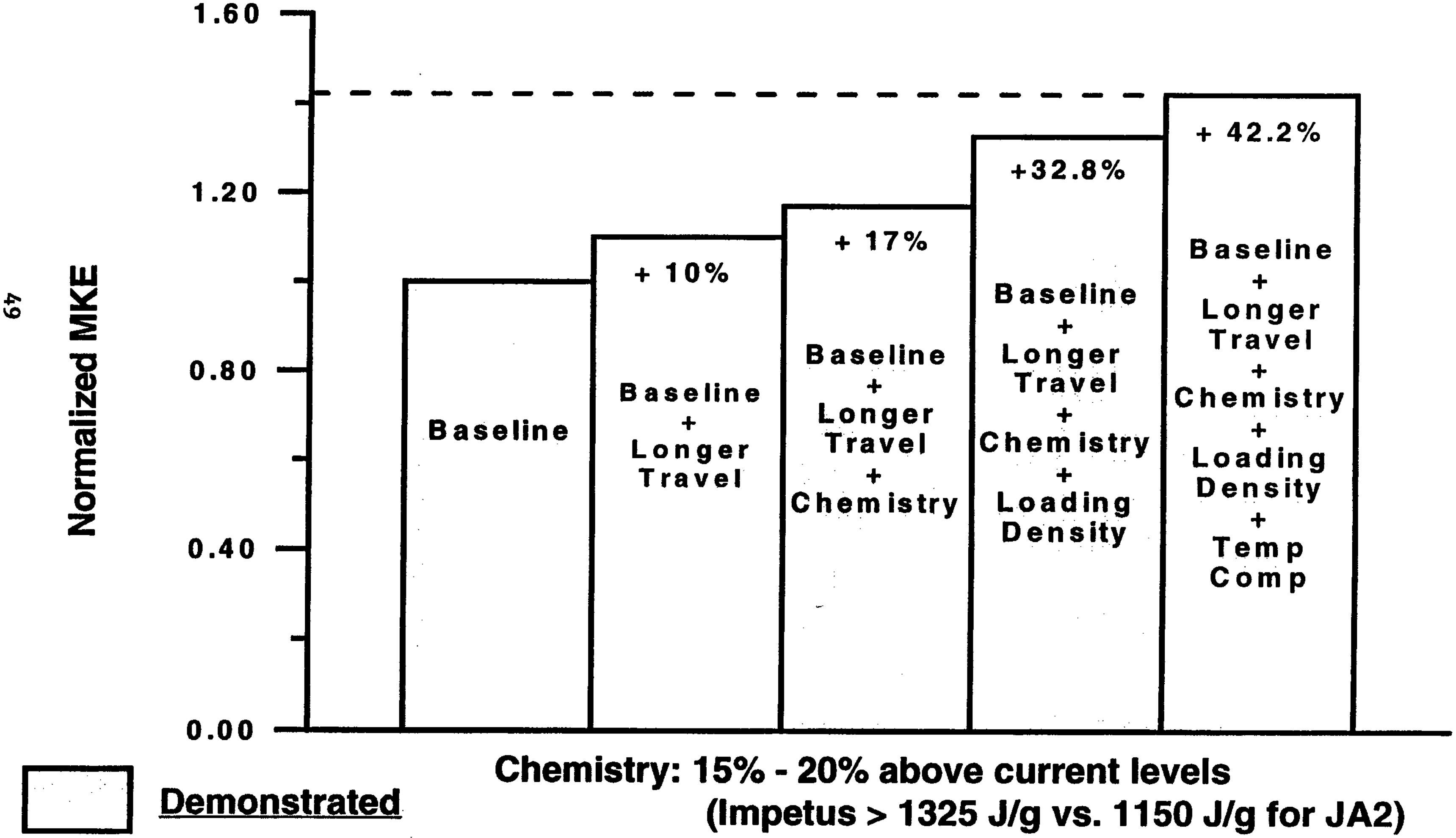
ETC – *minimize ignition variability*

- *Increase penetrator performance*



Approach To Achieving Desired Goal

Baseline: 120-mm M256 w/ advanced KE penetrator



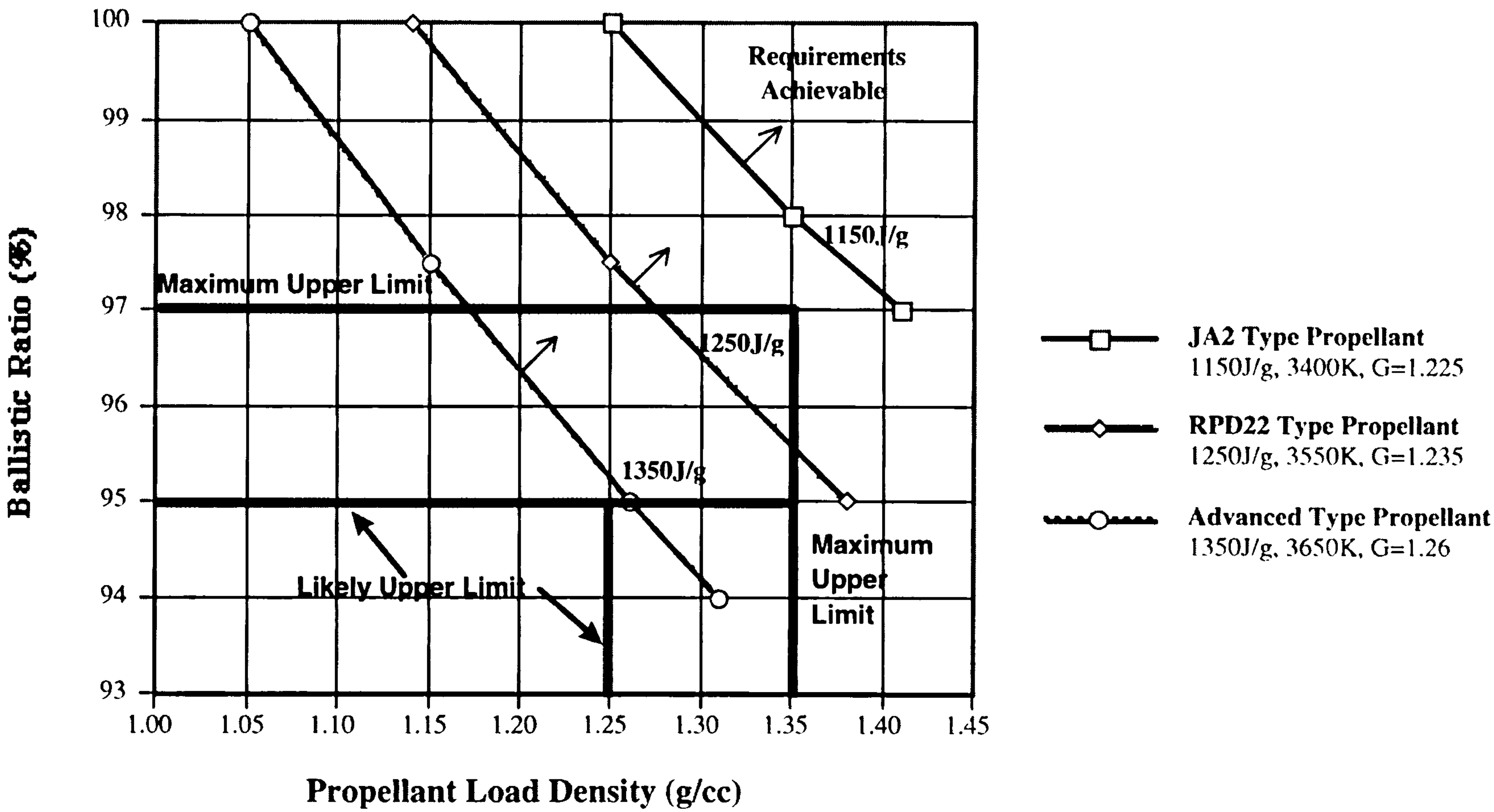
Chemistry: 15% - 20% above current levels
(Impetus > 1325 J/g vs. 1150 J/g for JA2)
Loading Density: 1.25 g/cm³ vs. 1.05 g/cm³ (adv. solids today)

DEA-G-1060/JAN98

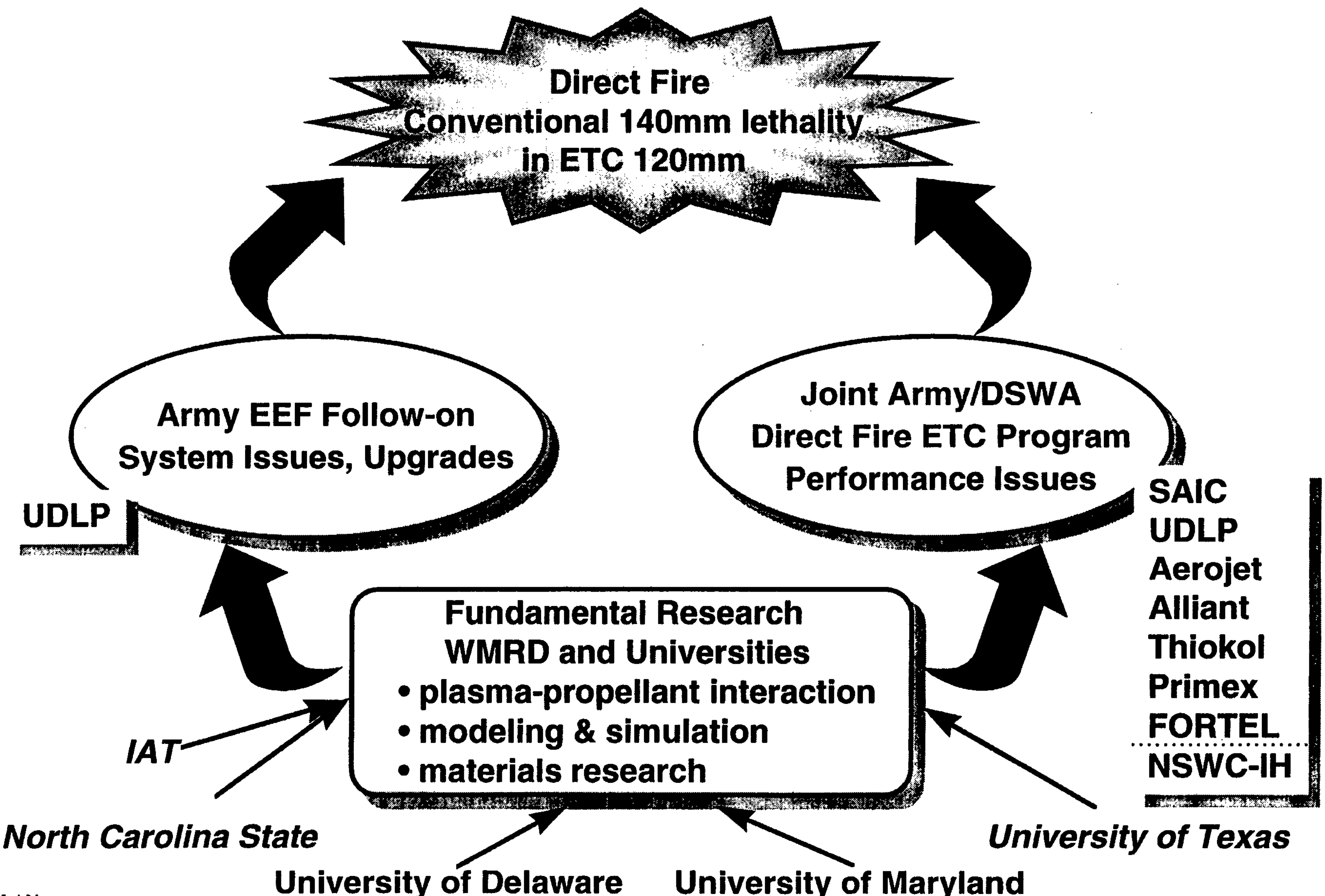
CONPRESS Requirements

Ballistic Ratio/CONPRESS Analysis of 17MJ Requirement

(120mm XM291 Barrel, 6.12m Travel, 725MPa Peak Pressure, 10.18Kg Proj., 8.1L/9.0L Volume)

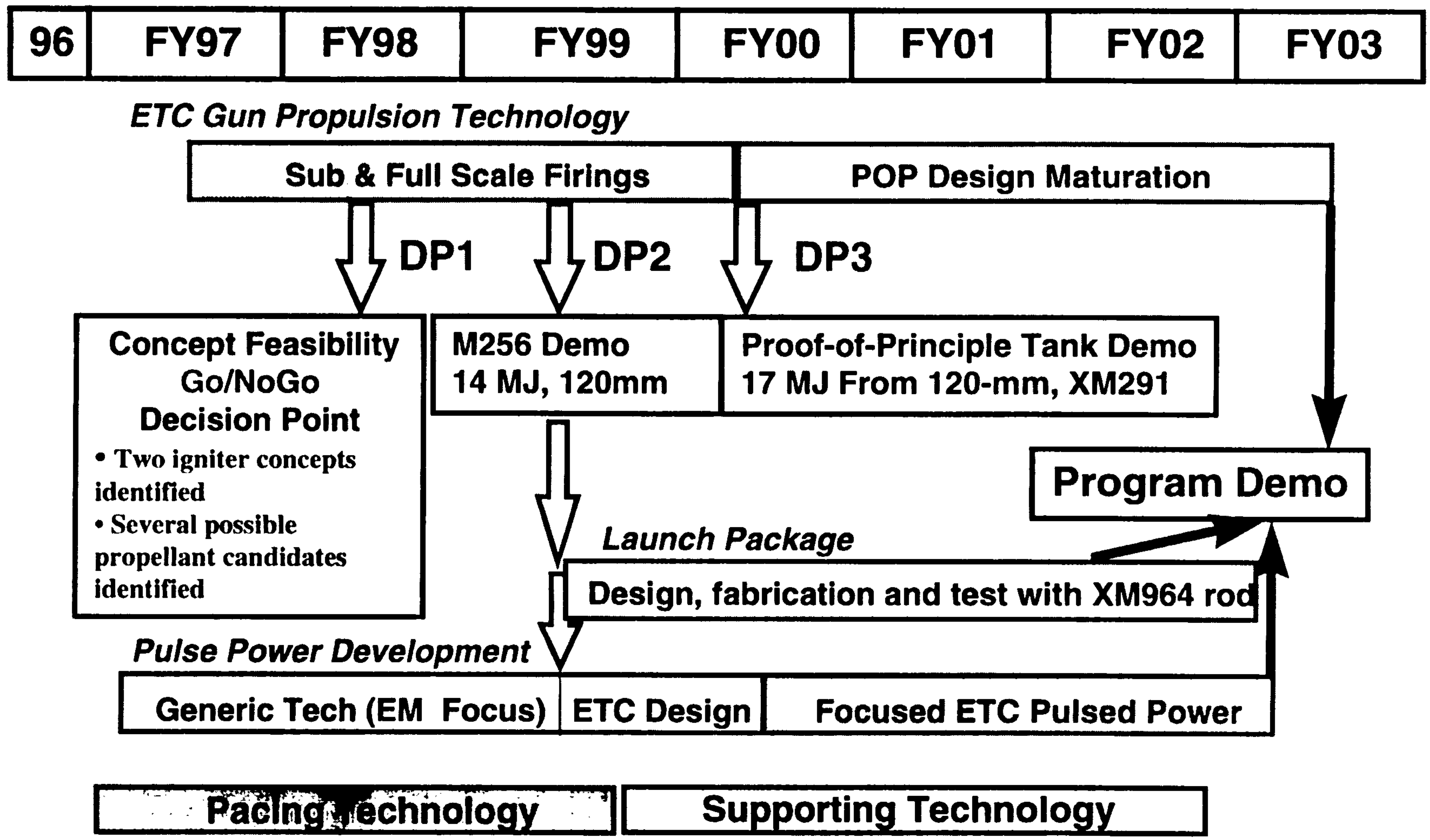


U. S. Army ETC Program Structure



FY99_PLAN

Joint Army/DSWA ETC Program



DEA-G-1060/JAN98

STATUS OF US PULSED POWER DEVELOPMENT

Dr. Ian R. McNab
University of Texas

Briefing to
German-US DEA-G-1060 Meeting
ARL/WMRD/APG Building 330

27-28 January 1998

UT-IAT 6.1 basic research program

- A significant fraction of the UT-IAT 6.1 program is pulsed power research and development
- This includes:
  - machine and switch development for the railgun
  - supporting the ETC program through power and plasma studies
  - development of alternate technologies, such as flux compressors
  - long term studies, such as HTSC development
- Only the ETC-related topics will be discussed today

Energy and power requirements for ETC

- Multiple requirements have to be supported by the pulsed power sub-system:
  - Provide instantaneous power to the gun breech for each shot
  - Provide instantaneous energy for each shot
  - Provide energy storage for multiple shots
  - Accept “average” power from a prime mover during recharge
  - Accept “average” power for sustained operation
- System requirements are important
  - Hardware must be robust and operate reliably
  - Maintenance and repair needs to be easy
  - No EMI on associated hardware or externally measurable
  - Thermal management should be a minimal system burden

Energy storage options and choices

Mechanism & device	Assumptions	Typical device energy density (MJ/m3)	Comments	Status
Electrostatic capacitor	High energy density plastic film 400V/μm and ε=10	7	Not yet feasible for > 1 MJ in a FCS	Attractive option for ETC but improvements would be beneficial
Inertial rotor generator	High speed rotor 1500kg/m3, 600m/s	135	Possible solution for railgun	Under development for railguns. Flywheels can go to higher speeds
Magnetic inductor	High field air-cored inductor B = 20T	160	Does not yet appear feasible. Opening switch needed	Could be possible if HTSC development occurs. LN_2 needed
Electrothermal battery	LIMS cells operating at 480 C	200	Low cell voltages require multiple series/parallel units	Could be an adjunct for energy storage with a capacitor bank/PFN
Magnetic flux compressor	High energy fuel/air combustion-driven system	100	Prior efforts related to short pulse applications.	Further development needed. Possible for ETC-I

Energy and power requirements

Electric gun type	Energy input per shot (MJ)	Peak current (kA)	Peak voltage (kV)	Pulse length (ms)	Minimum ave. instantaneous power (GW)
EM railgun	40	4000	10	6	7
ETC gun	4	150	16	4	1
ETC igniter	0.4	50	10	1	0.4

Power train options - general comments

- Prime power will be provided by vehicle turbine or diesel engine
- Energy storage may be provided by:
  - capacitors
  - rotating generators
  - batteries
  - flywheels
  - or a combination of these
- Capacitors will store energy for only one shot
- Silent mode operation will require battery or flywheel storage for several shots without operation of the prime mover
- An inverter/converter will be needed to charge the capacitors
- Capacitors and generators can drive the gun directly

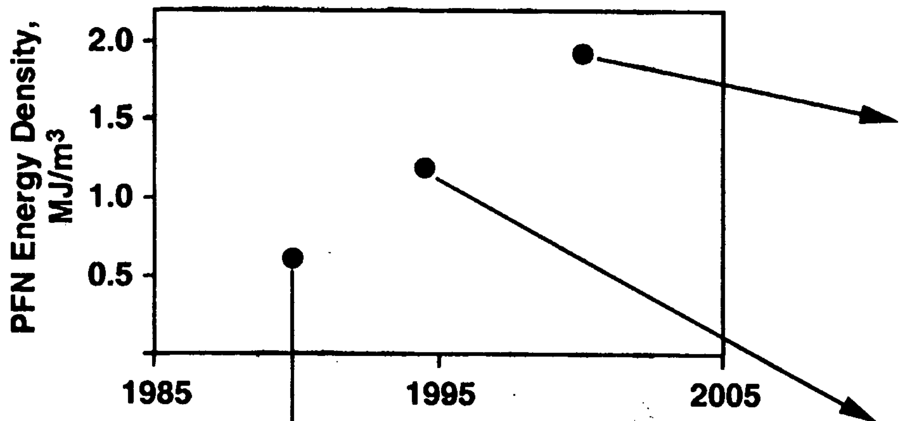
Possible power train for ETC-I system

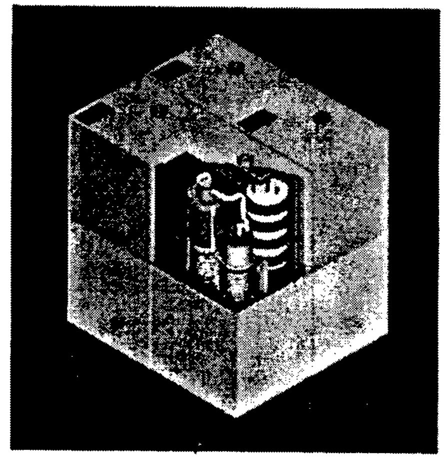
- Alternator connected to engine shaft will provide AC power
- Rectifier will transform AC -> DC for input to converter
- DC:DC converter will transform up to x kV for PFN charging
  - for steady state operation charging rate will support the required firing scenario
- The PFN capacitors will store energy for only one shot
- Some energy reserve for short-term rapid fire or silent mode operation will be provided by batteries or a flywheel-generator
  - low voltage DC will be required to charge the batteries
  - a (permanent magnet ?) motor will spin up the flywheel
- The battery or flywheel-generator output will be inputted to the converter to charge the capacitors
- Intelligent energy management with other vehicle electrical loads (drive, EM armor, HPM, DEW, EM suspension, APS) will be needed

ETC-related 6.1 R&D

- PFN components
  - capacitor dielectric development supported jointly with DSWA
  - compact inductor development with PI - now terminated
  - high efficiency DC:DC converter development with SAIC
- Switches
  - TVS development underway at PI
  - fundamental vacuum switch investigations at TTU
  - operating limits of pulsed thyristors investigated by ARL
  - hybrid switch concepts under study at UT-CEM
  - improved SiC materials under development at ARL/Delaware
- Alternate technologies
  - feasibility demonstration of flux compression generator
  - improved HTSC materials at UT

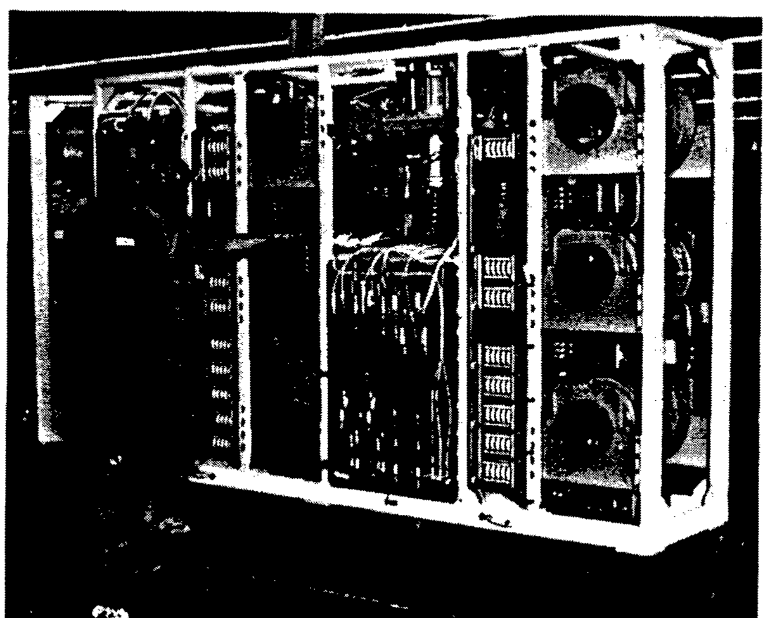
PFN System Volume Trends





1.0 MJ Advanced PFN

Circa 2000
2 MJ/m^3



2.2 MJ ARDEC Pulsed Power Module

S.O.A. ~1990
0.5 MJ/m^3

1.0 MJ High Density PFN Concept

S.O.A. ~1994
1.25 MJ/m^3

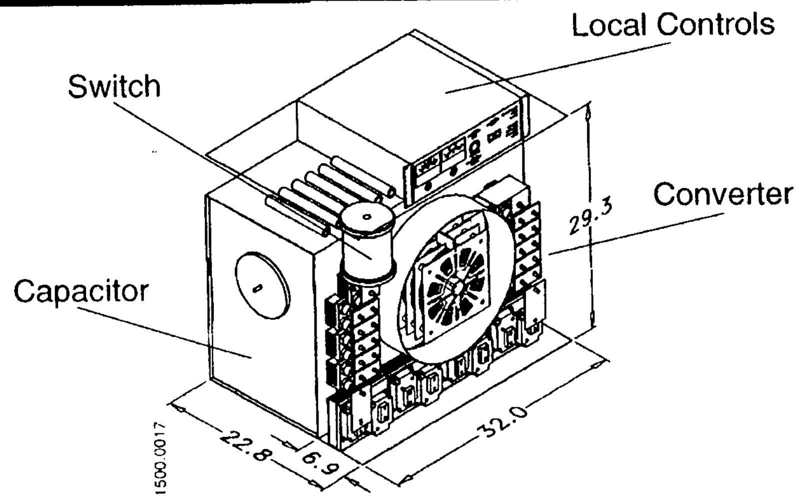
8086-94-03 Gilman

Improved Dielectrics

- Capacitors are the largest contributor to PFN system size and mass
- The energy stored in a dielectric ~ εE^2 — see table below
- New dielectric materials would be advantageous
  — energy storage for only a few seconds is necessary [Marshall]
- The size and weight of other system components should be minimal
- Integrated PFNs can combine functions
- Ruggedization and easy maintainability for field use is essential

Material	Dielectric Constant	Breakdown Voltage (V / mm)	Stored Energy Density (MJ/m^3)	Comment
Polypropylene	2.1	200	0.37	**Well-characterized Linear material**
Polyethylene	3.25	300	1.3	**Well-characterized Linear material**
Polyvinylidenefluoride	10	400	7	**Minimal characterization Non-linear material**

High Efficiency Lightweight PFN Charger Investigation



Breadboard PFN/Converter (dimensions in inches)

CONTRACT

- Contractor: SAIC
- PI: Dr. Walter Crewson
- Objectives: Analyze options for a high efficiency lightweight 300 V - 6,000 V DC-DC converter to charge a PFN.

  Select preferred geometry & components.

  Undertake detailed design, fabrication & test.

  Assemble & test complete breadboard system.

ACCOMPLISHMENTS

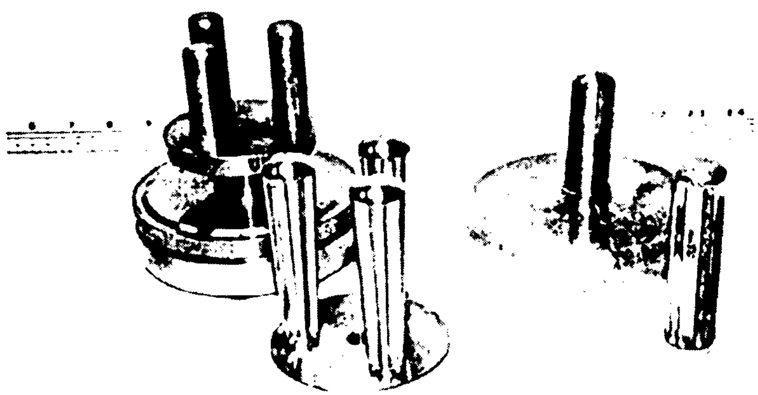
- Flyback converter concept chosen for high efficiency operations.
- IGBT's (Integrated Gate Bipolar Transistor) selected for switching
- Two inductor designs completed.
- Converter components procured and assembly taking place.
- Battery & PFN components identified and in procurement.

FUTURE PLANS

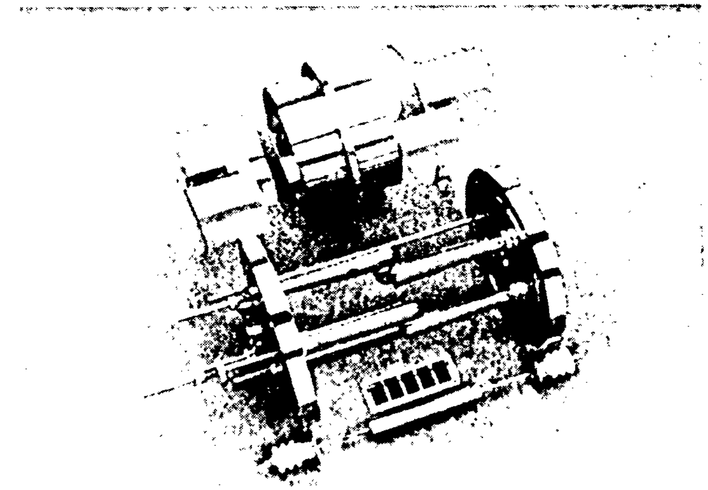
- Complete assembly & test of flyback converter.
- Assemble & test breadboard PFN system at SAIC.
- Deliver converter to ARL for test & evaluation.

vg 6176

TVS structure and tests



TVS electrode geometries

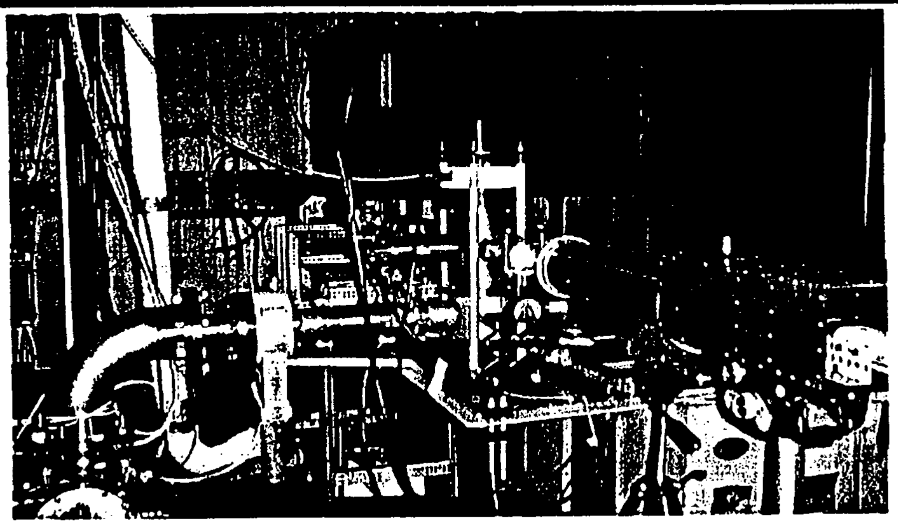


PRIMEX PI switch structure

Test geometry

Switch under test

Vacuum switch development


TVS test stand with Schlieren set-up

CONTRACT SUMMARY

Contractor: Texas Tech University

PI: Dr. James Dickens
Prof. M. Kristiansen

Objectives: Determine the physical processes and plasma parameters that govern rod array vacuum switch performance

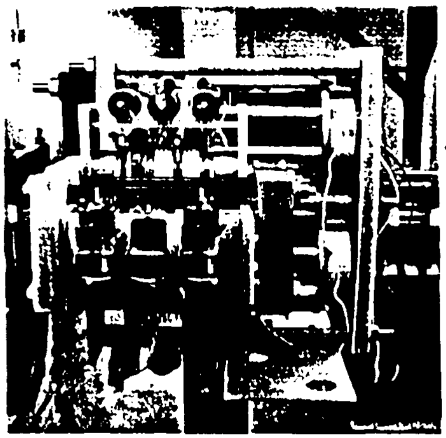
ACCOMPLISHMENTS

- Actively pumped, demountable, optically accessible test facility built and operated
- Self break data obtained at high voltages with C300 & T300 electrodes
- Obtained sub-μs image intensified photos near & at current zero
- Schlieren photography undertaken at peak current

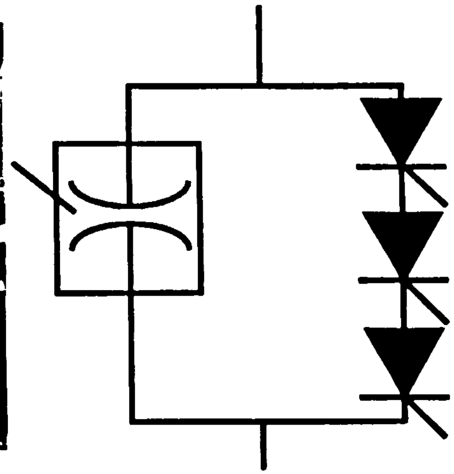
FUTURE PLANS

- Complete line spectroscopy measurements with optical multi-channel analyser
- Perform laser-induced fluorescence measurements to obtain plasma parameters of neutral metal vapor at current zero
- Apply analysis of data to design of next generation TVS

Hybrid switch development



Series diode test



Parallel circuit

CONTRACT SUMMARY

Contractor: UT-CEM

PI: J.Pappas/J.Kitzmiller

Objectives: Develop, test & characterize hybrid switch concepts having fast turn-off (high dI/dt) and high current capability with minimal parts count

ACCOMPLISHMENTS

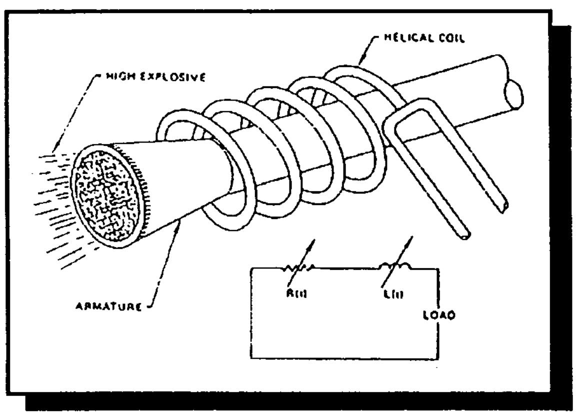
- Project established at UT-CEM
- Experimental facility ready for tests
- Design and analysis of first concept completed - TVS plus series diodes
- Equipment in ready for initial tests
- Second concept - parallel SCRs - appears attractive in analysis

FUTURE PLANS

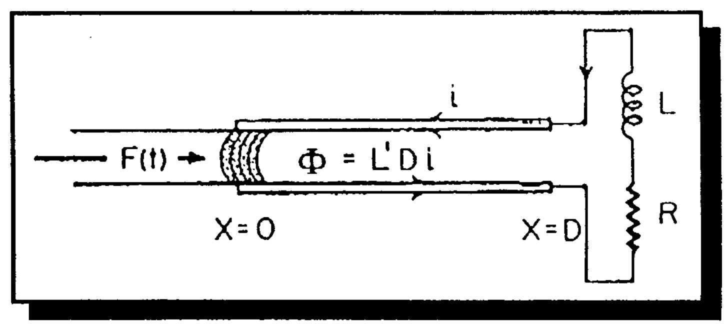
- Initial tests planned for October at CEM uses TVS-40 and series diodes
- Second concept using parallel SCR will be evaluated further, built and tested
- Data obtained will be evaluated for applicability to ECM

Linear Magnetic Flux Compressors

- Possible alternative to rotating machines and capacitors
- I > 250 MA has been achieved using explosive-driven conductors
- Efficiencies are low (< 10%) and pulse lengths are a few 10s μs
- Ordnance electric guns need pulses of a few ms.
  - — increased losses may reduce efficiencies
  - — should not require more explosive than a powder gun
- An efficient fuel / air combustion system may be possible



1200.0866



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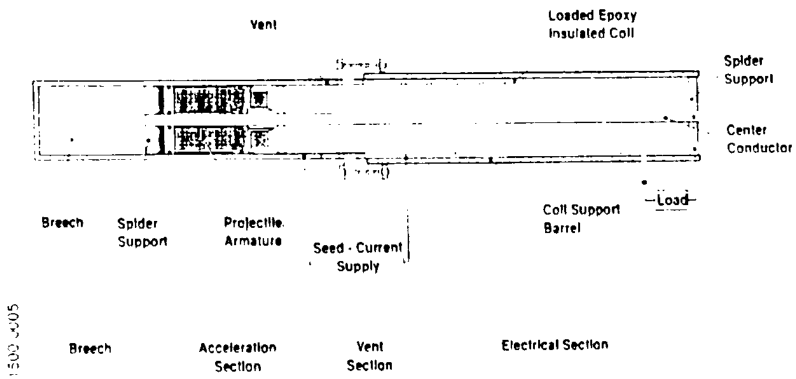
Feasibility Demonstration of a Flux Compressor Power Unit



Overall Configuration

ACCOMPLISHMENTS

- Simulation code used to assess performance and create preliminary design concept
- ETC(I)-rated capability predicted for a 120-mm dia. 900 m/s ICFC system
- Detailed design created using some existing components
- CDR held 10/28/96 at Socorro with IAT / ARL / ARDEC
- Components in final stage of manufacturing
- Calibration tests undertaken to determine propellant loading

CONTRACT

- Contractor: ST&A / Ktech / NMT
- PI: Dr. Ed Goldman
- Objectives: Evaluate feasibilityof inverse coilgun flux compressor (ICFC) to power an ETC(I) load. Build and test a unit to demonstrate high current and energy multiplication.

FUTURE PLANS

- Complete testing and data analysis
- Test into ETC(I) representative load
- Develop and test improved armature design
- Develop and test improved brush design
- Continue code development and performance predictions
- Initiate system level trade analysis for FCS-like conditions, identify critical technology shortfalls and create a technology roadmap

vg 6164

Summary

- 6.1 component developments for ETC guns are currently focussed on PFN's for single shot energy storage
- Switch technology developments can support railgun and ETC applications
- Alternate concepts, such as flux compressors, are likely to be best suited to ETC-I applications
- No flywheel or battery technology development is presently being supported in this 6.1 program
- More focussed developments will be needed to optimize the ETC power system

Electric Energy Storage & Pulse Power for ETC Activities of Magnet-Motor GmbH

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Magnet-Motor GmbH
Petersbrunner Strasse 2
D-82319 Starnberg, Germany
Phone: +49-8151-262.170
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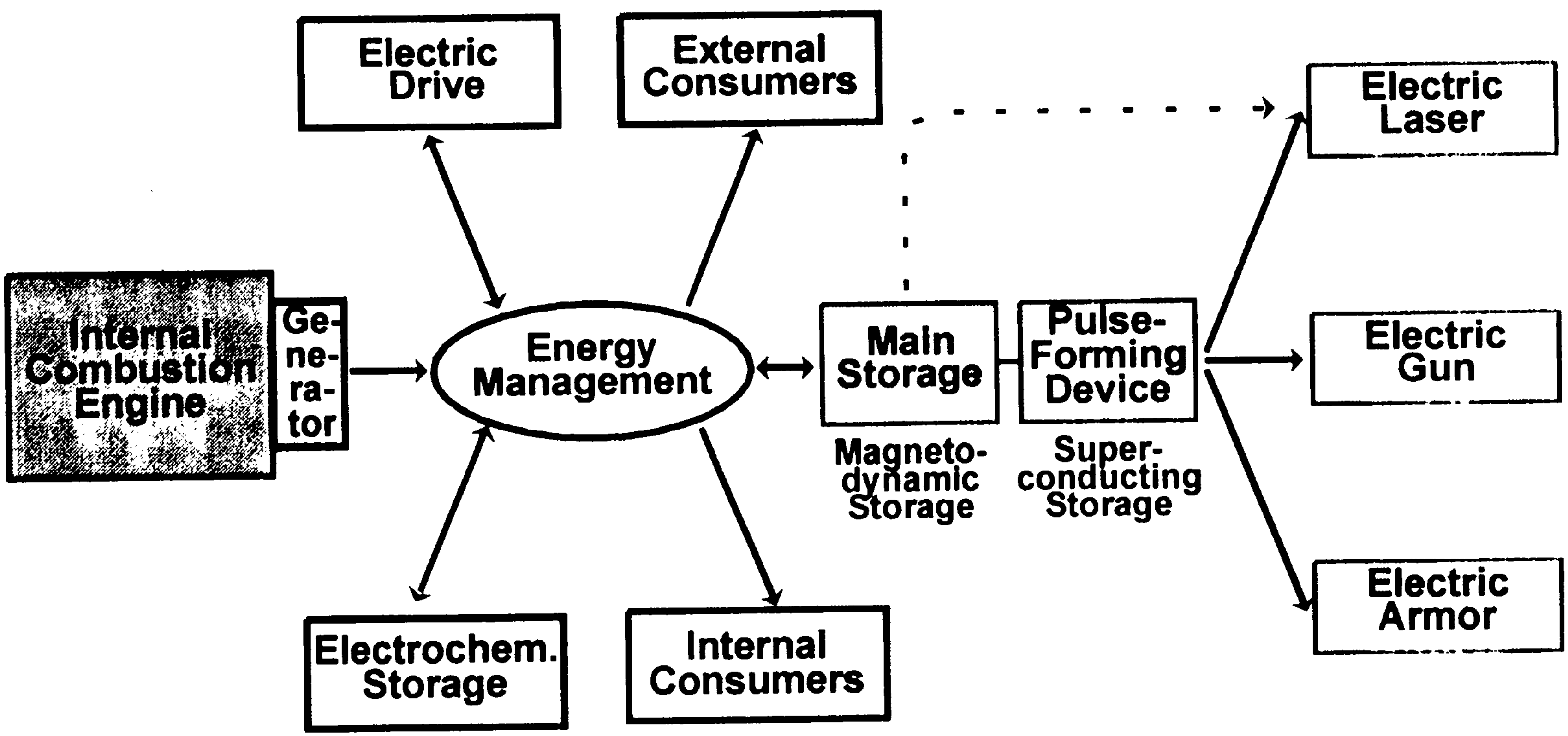
Bloc Diagram of a Future All Electric Vehicle Energy Generation- and Storage System and Consumers

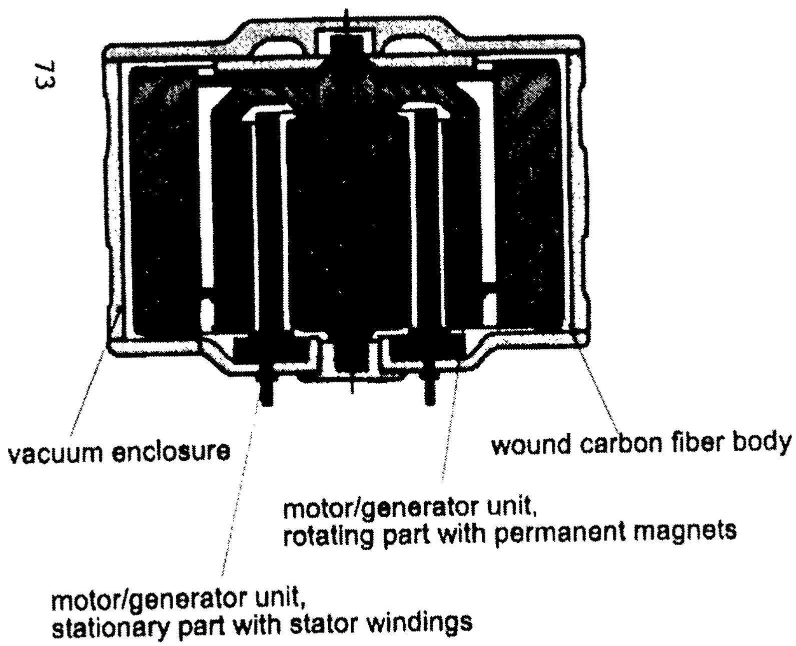
MAGNET MOTOR



Magnetodynamic Storage (MDS)

MAGNET MOTOR

Flywheel energy storage for electric drive system and electric weapons in an All Electric Vehicle

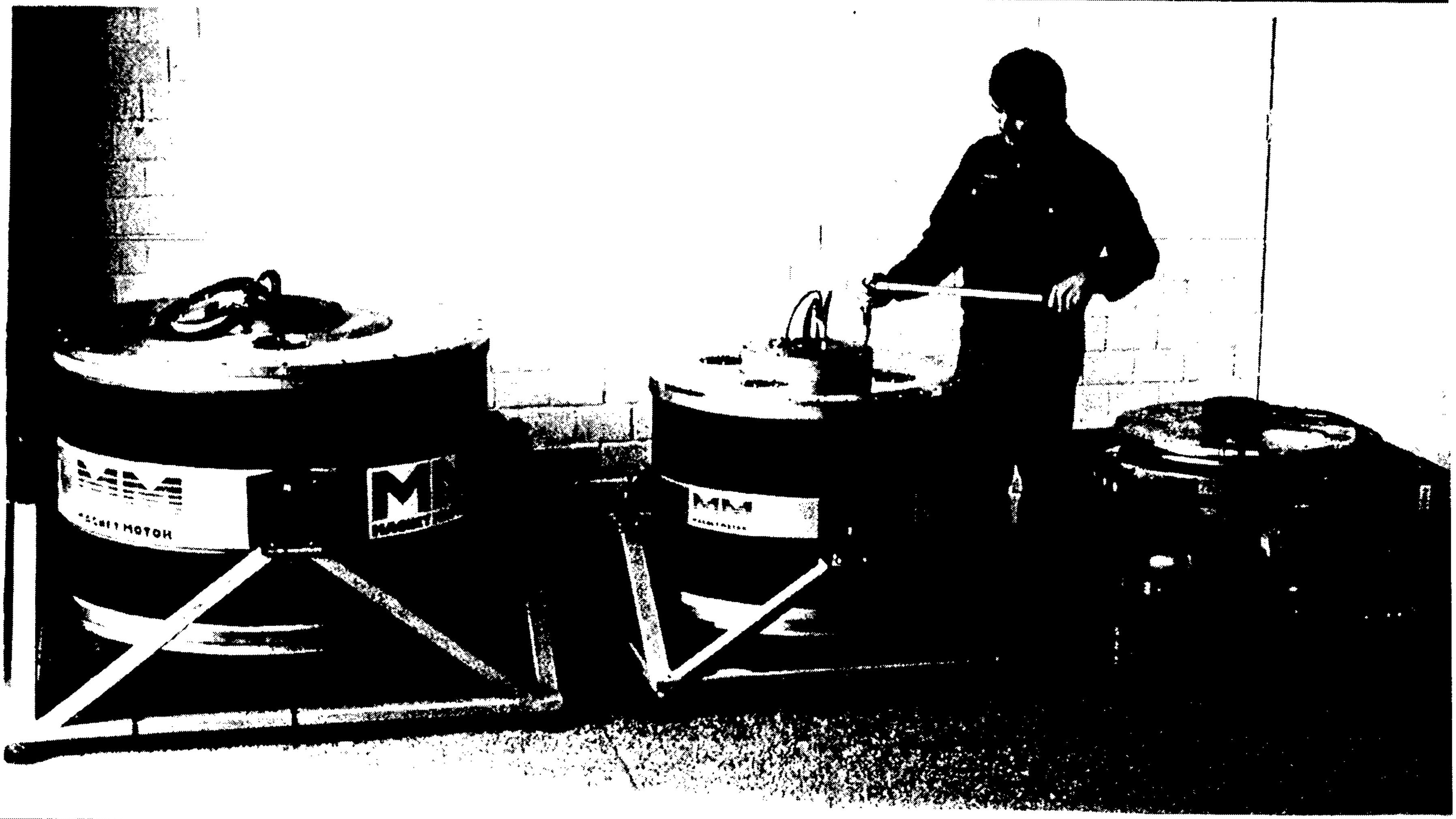


- high power and energy density
- extremely high cycle numbers
- high efficiency values at full and partial load
- automatic charge and discharge operation
- integrated design without mechanical feedthroughs and without gear

Typical Peak Power Situations

MAGNET MOTOR

- ❐ Peak levelling and stabilizing the on-board power supply system
- ❐ Charging the pulse storage of an electric gun
- ❐ Acceleration of the vehicle
- ❐ Supplying other weapon systems with electric energy
- ❐ Supplying additional consumers



Magnetodynamic Storage MDS

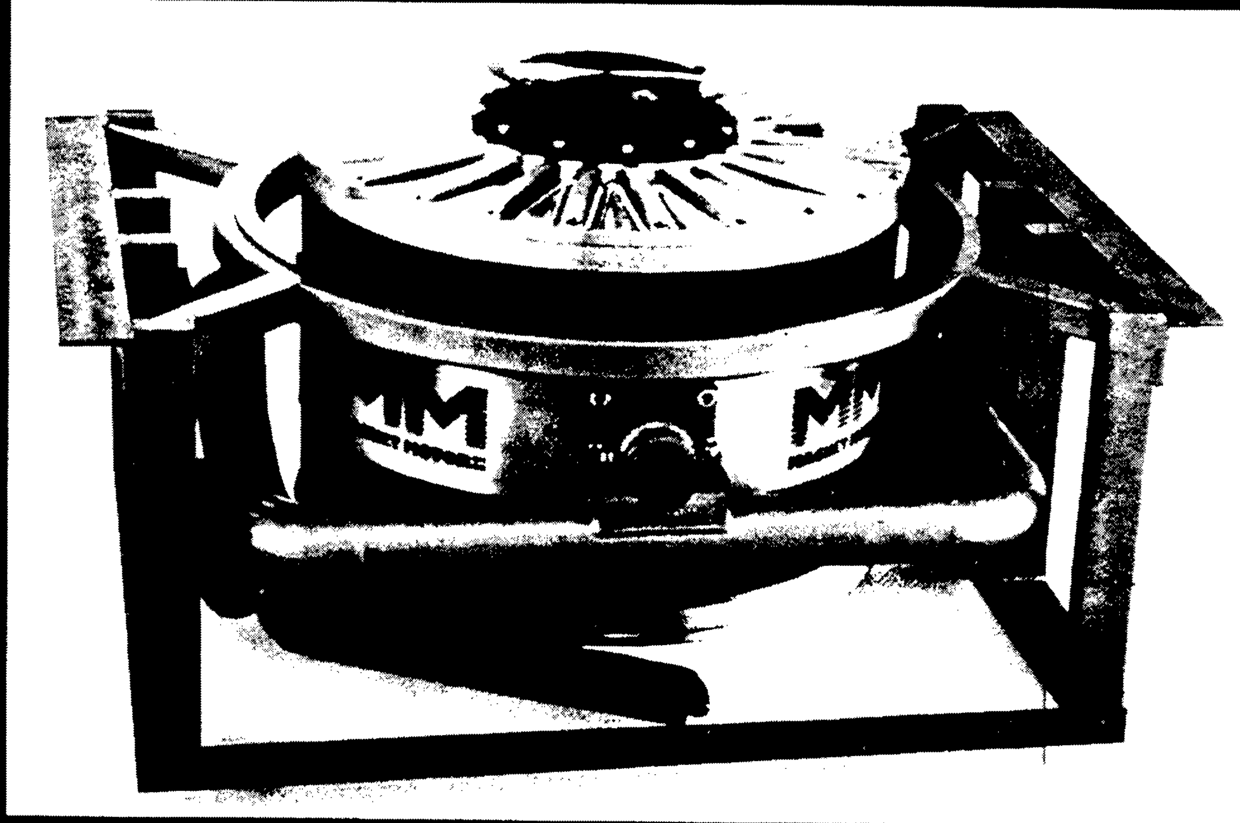
left side: Test stand unit for demonstration of 80 MJ / 5 MW (1994)

middle: Test stand unit for demonstration of 80 MJ / 2,5 MW (1996)

right side: Small lot production unit for application in urban buses

MAGNET MOTOR

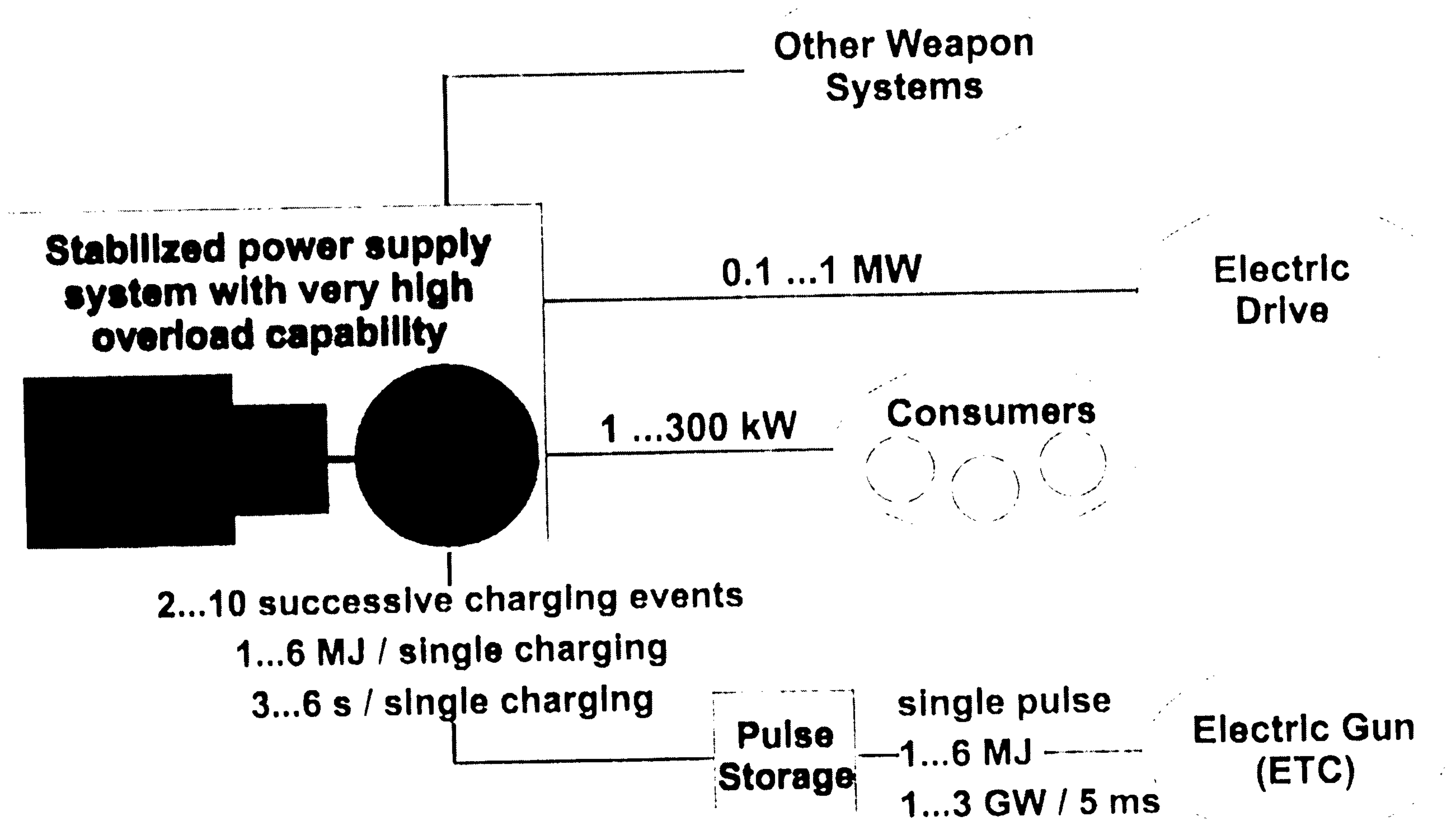
design data		MDS-K	MDS-L1	[redacted]	
energy	E =	7.2	78	[redacted]	MJ
max. power	P =	0.3	5	[redacted]	MW
max. voltage	U =	650	500	[redacted]	V
max. current	I =	0.5	12	[redacted]	kA
speed	n =	12,000	8,800	[redacted]	1/min
diameter	D =	620	1,250	[redacted]	mm
axial length	H =	650	950	[redacted]	mm
volume	V =	0.19	1.17	[redacted]	m^3
weight	m =	0.4	2.1	[redacted]	t
spec. energy:	e =	18	37	[redacted]	MJ/t
spec. power:	p =	1.0	2.4	[redacted]	MW/t



Magnetodynamic Storage MDS K

Since 1988 operated in dieselelectric and trolley buses

Requirements of an Electric Combat Vehicle on its Power Supply



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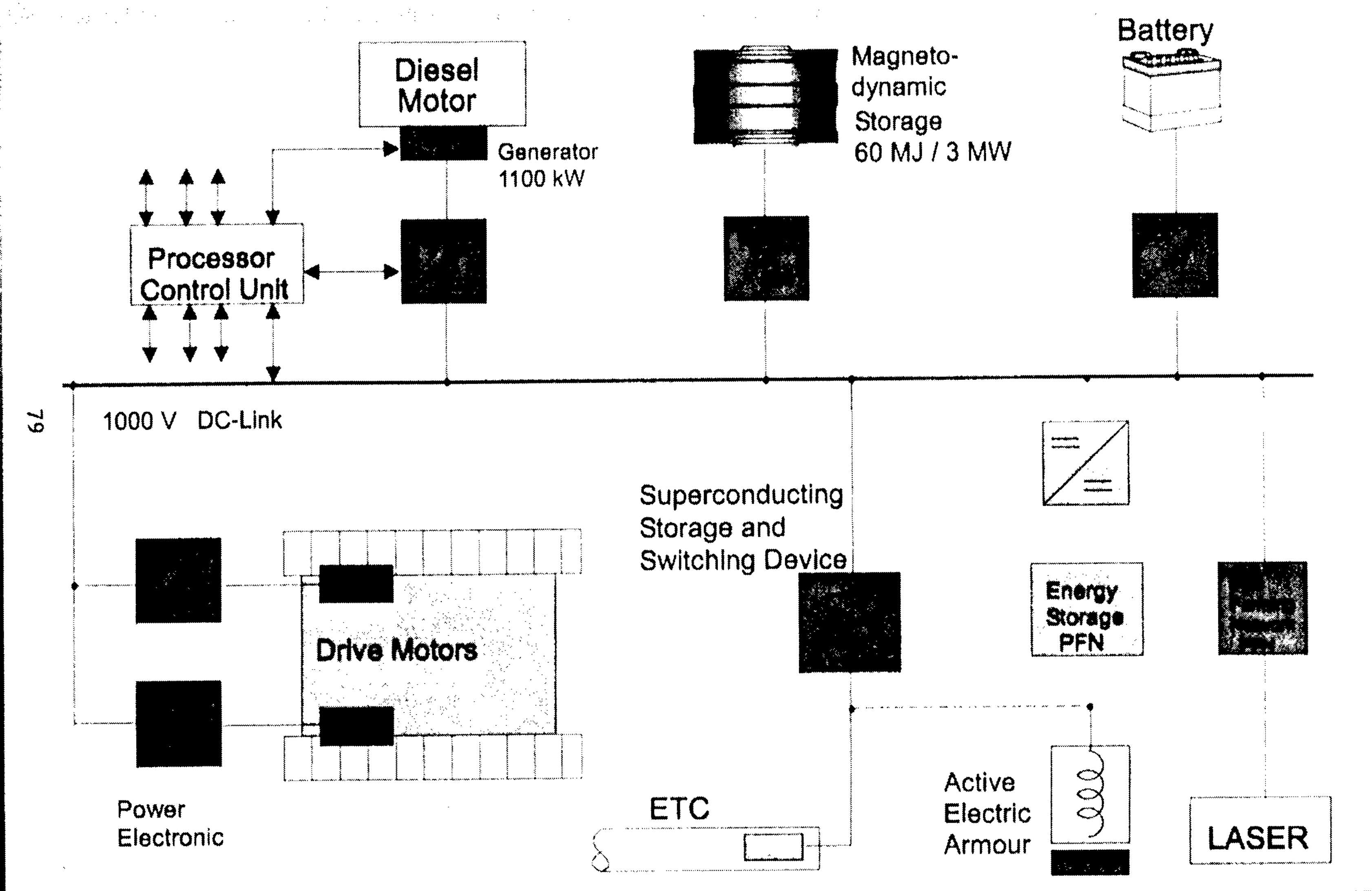
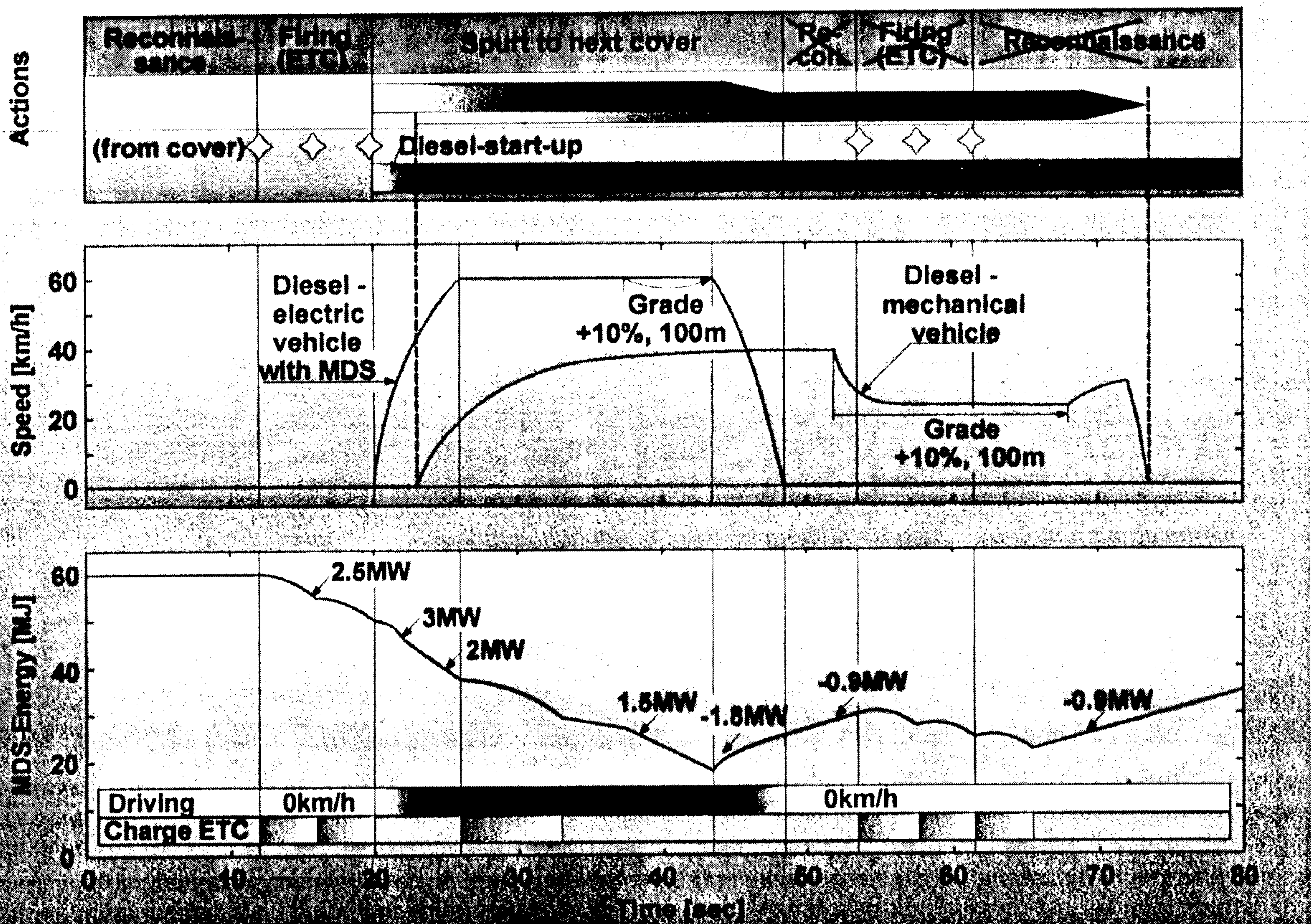
Block Diagram of the Electric Power Circuit of an Electric Combat Vehicle



Contribution of an MDS to the Tactical System Performance

- The MDS replaces or augments the diesel-generator unit for seconds up to minutes
- Up to 4 MW system power is made available for a short period of time
- The MDS is integrated in the power DC-link of the vehicle and can supply the whole electric vehicle system

Example Scenario Electric Tank and Conventional Tank



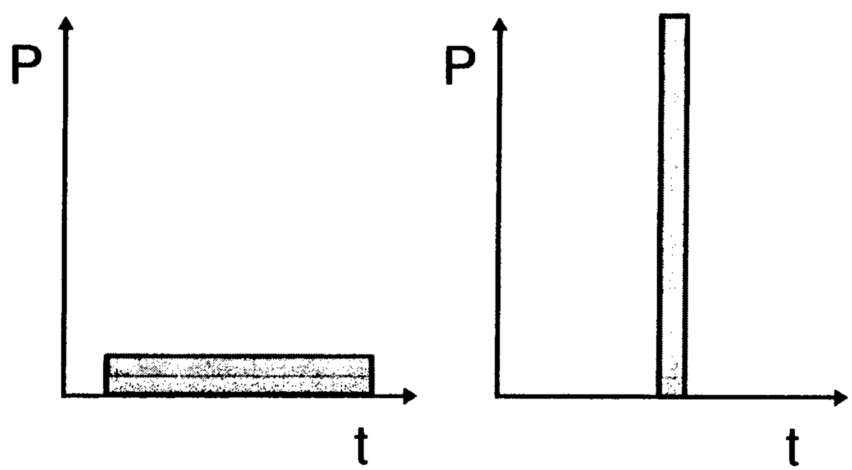
Summary

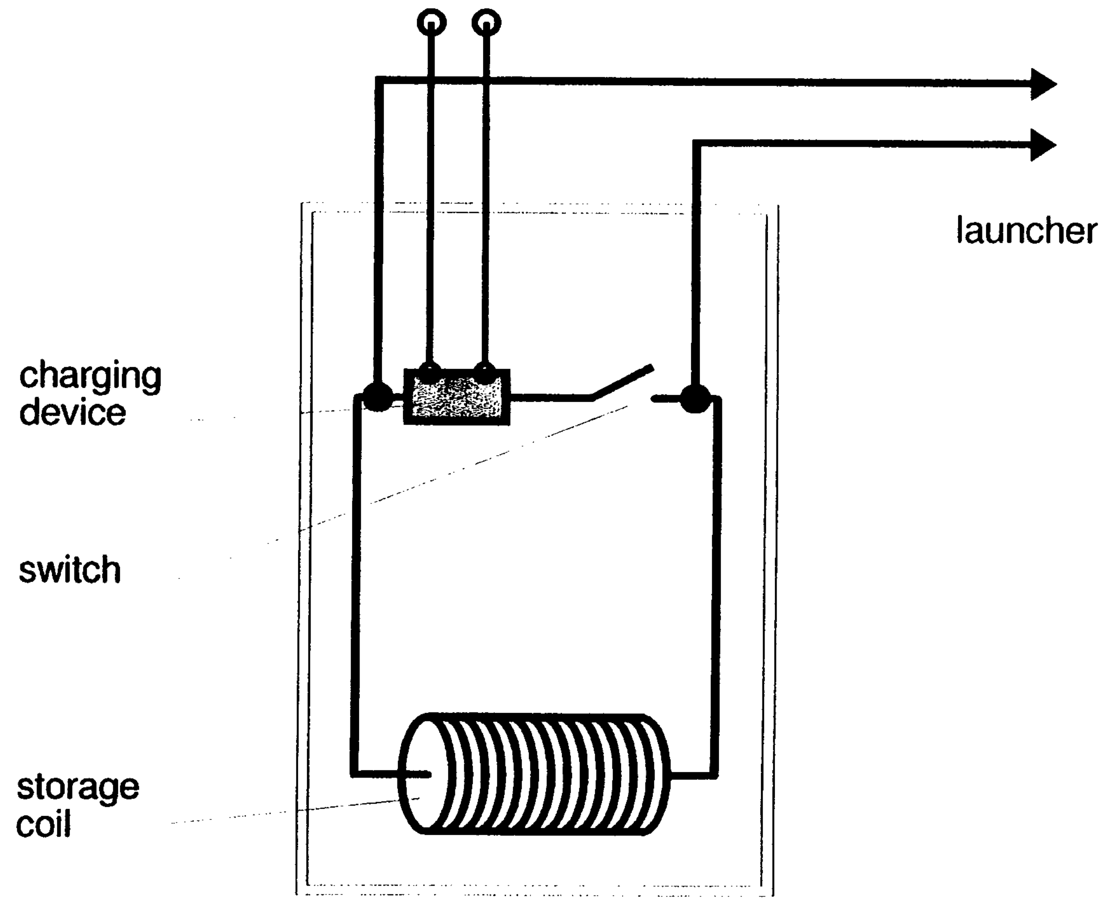
MAGNET MOTOR

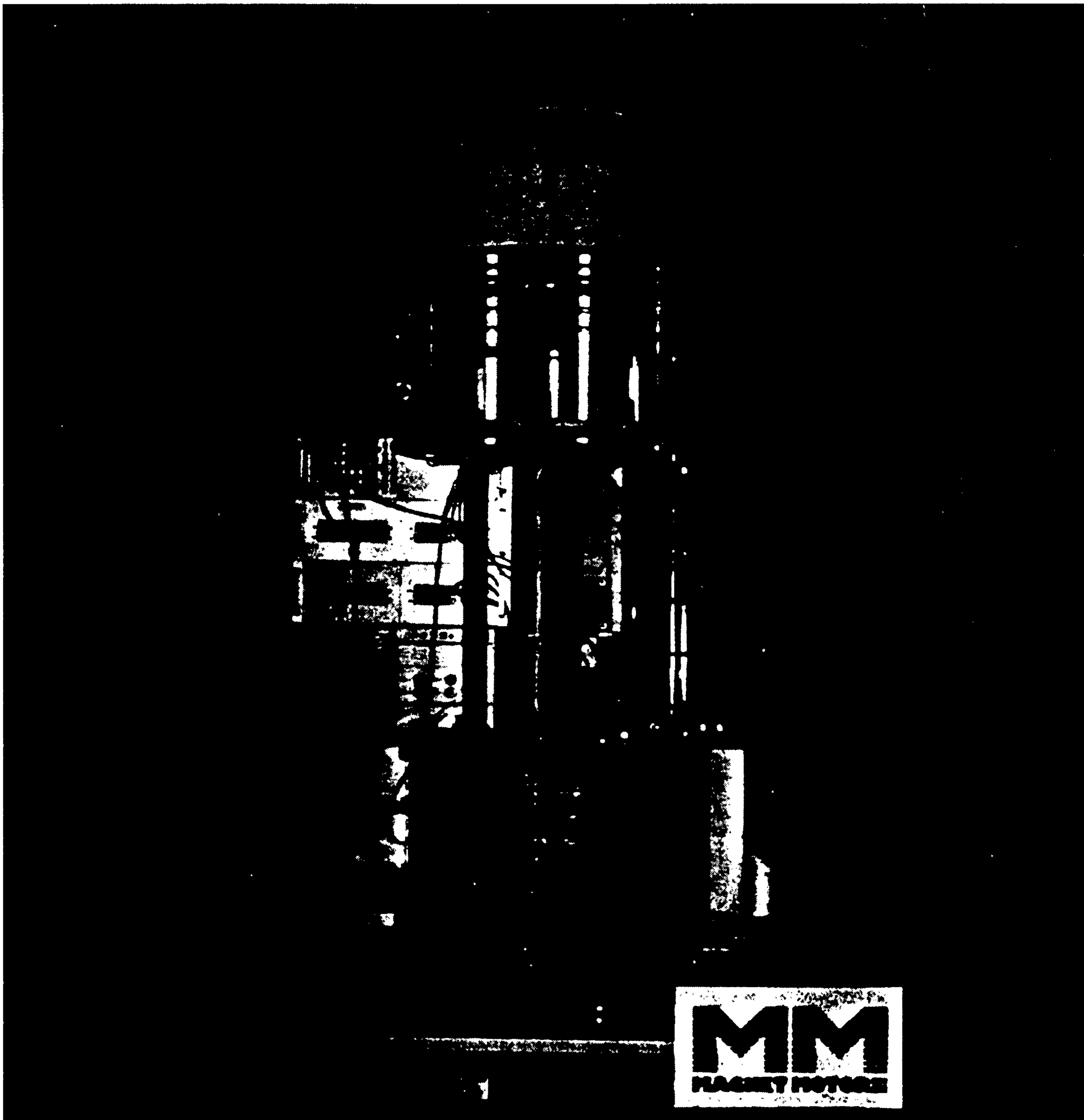
- In the past 10 years MDS - systems have proved their functionality and reliability in every-day use in urban buses
- MDS provides a stabilized on-bord power supply with high peak power capability
- MDS-output can be used for ETC - recharging as well as for the electric drive system and other consumers
- MDS gives drastic advantages in the mobility of the vehicle
- MDS increases considerably the tactical system performance of the vehicle and it opens up new opportunities.

Superconducting Inductive Pulse Power Supply

Function Principle

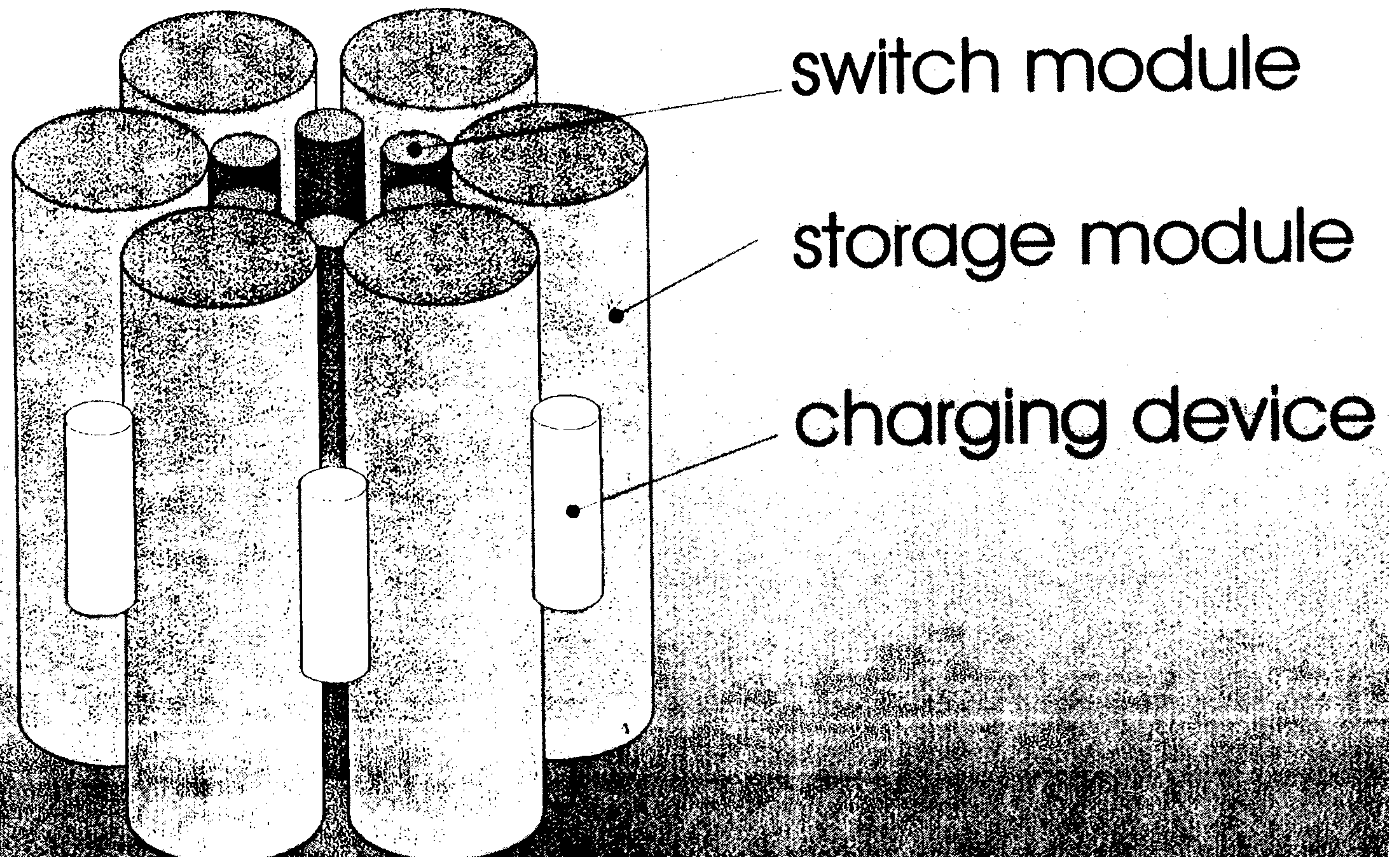






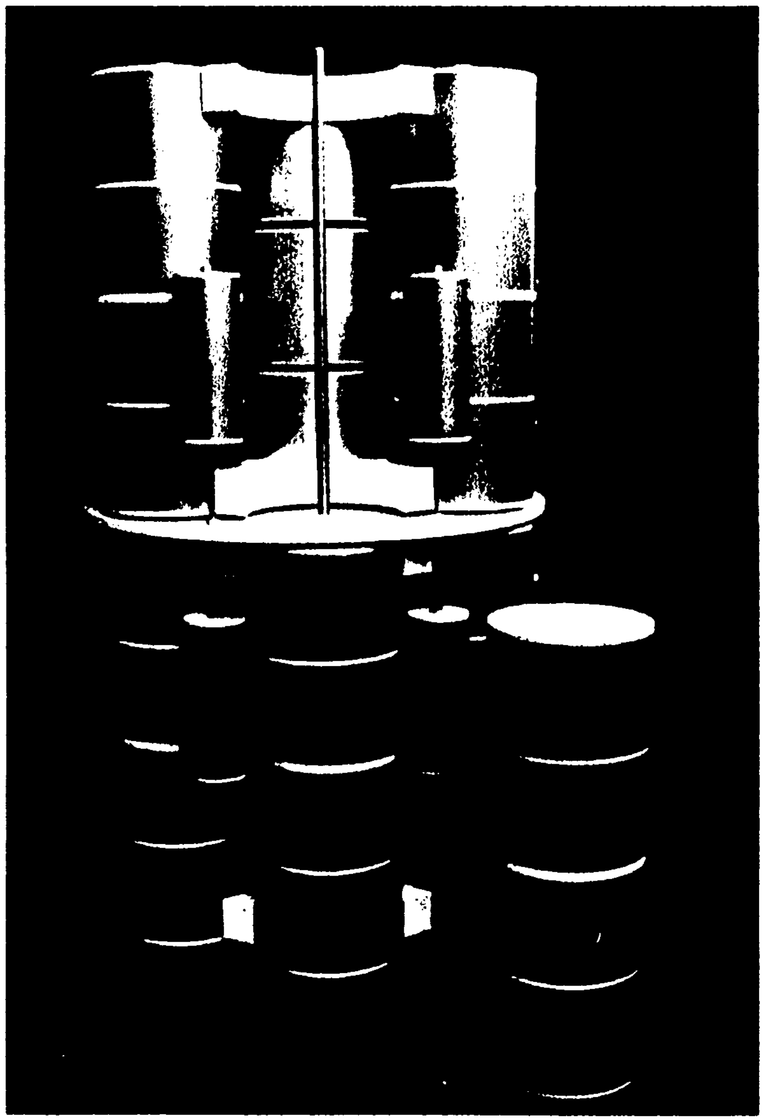
SCS-unit (24 modules), test assembly

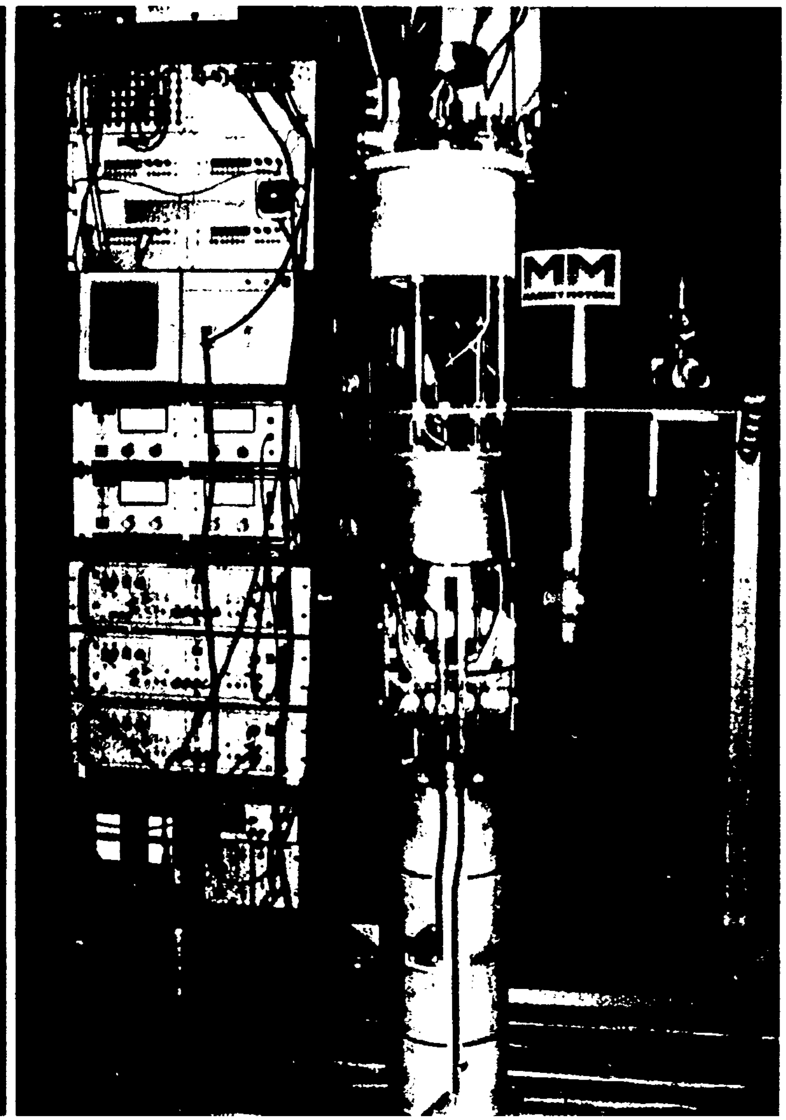
Superconducting Inductive Pulsed Power Supply



Superconducting Inductive Pulse Power Supply

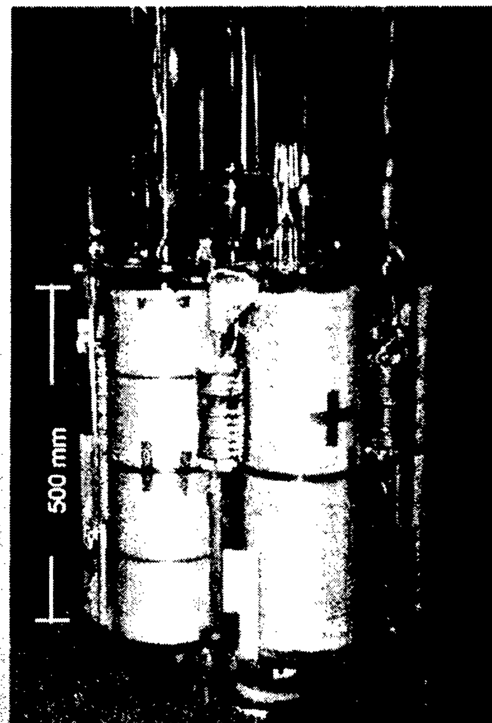
MAGNET MOTOR

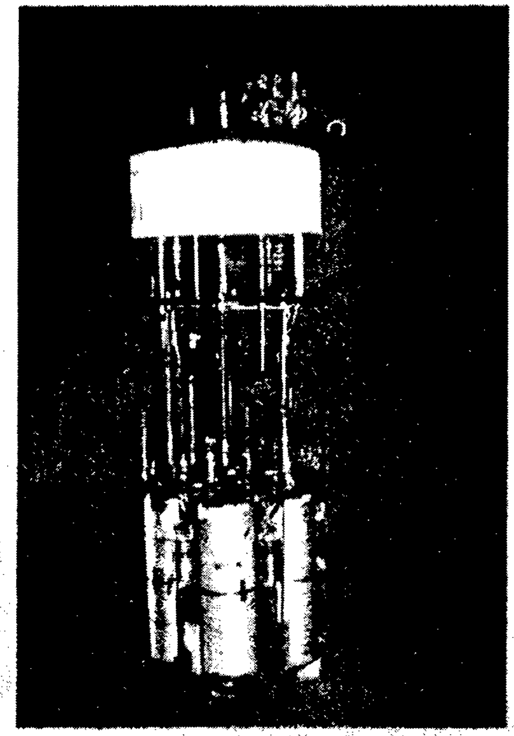




Superconducting Inductive Pulse Power Supply

MAGNET MOTOR





Laboratory tests of superconducting pulse power supply

Half of original arrangement of NbTi coils (first step of completion)

Performance:

- Energy 500 kJ
- Power 20 MW

22.05.97

Closed vessel experiments:

- Experimental results indicate very good compatibility of inductive storage and ETC
  →decreasing current and increasing voltage match for "rectangular" power
- Experimental demonstration of pulse forming features by time controlled discharge of modules
- Limitation of peak power at present due to laboratory equipment (not a matter of superconductor principle)

High Temperature Materials Research with Metalized-SiC for Pulsed Power Electric Guns

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Prof. James Kolodzey
Department of Electrical and Computer Engineering
The University of Delaware, Newark, DE 19716

Outline

- ✦ Background\Objectives
- ✦ Experimental results
  - → electrical characterization of high temperature materials
- ✦ Summary

Background/Motivation

- Electric (tank) gun systems become more viable with increasingly compact pulsed power systems
- Advances in high temperature electronic materials could significantly reduce pulsed power system mass and volume

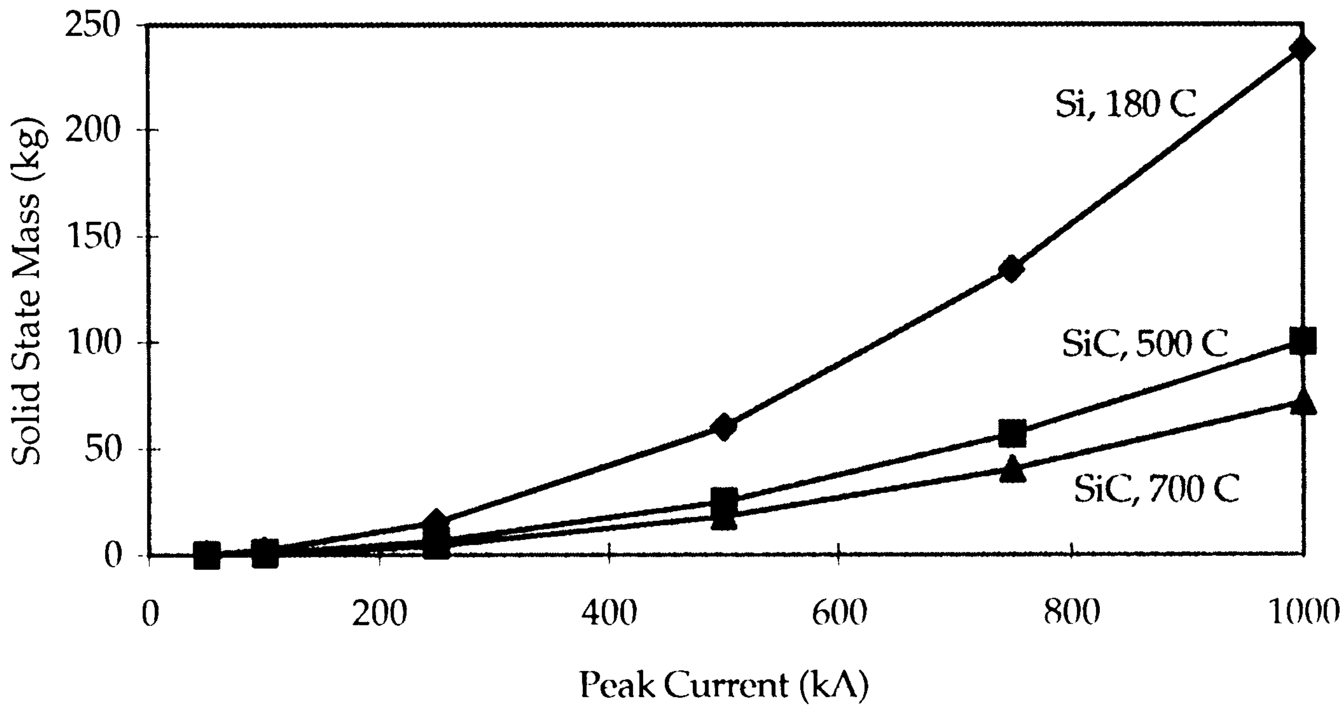
    (solid state switch mass > 20% of total system mass)

- Candidate electronic material: silicon-carbide (SiC)

pros	cons
* high voltage capability	* crystal defect density
* high current capability	* processing difficulties
* high thermal conductivity	* immature technology

Potential Benefits of High Temperature Materials

Mass Vs peak current for 3ms power pulse width



- Reduced solid state material mass by as much as 55-65%

Technical Objective

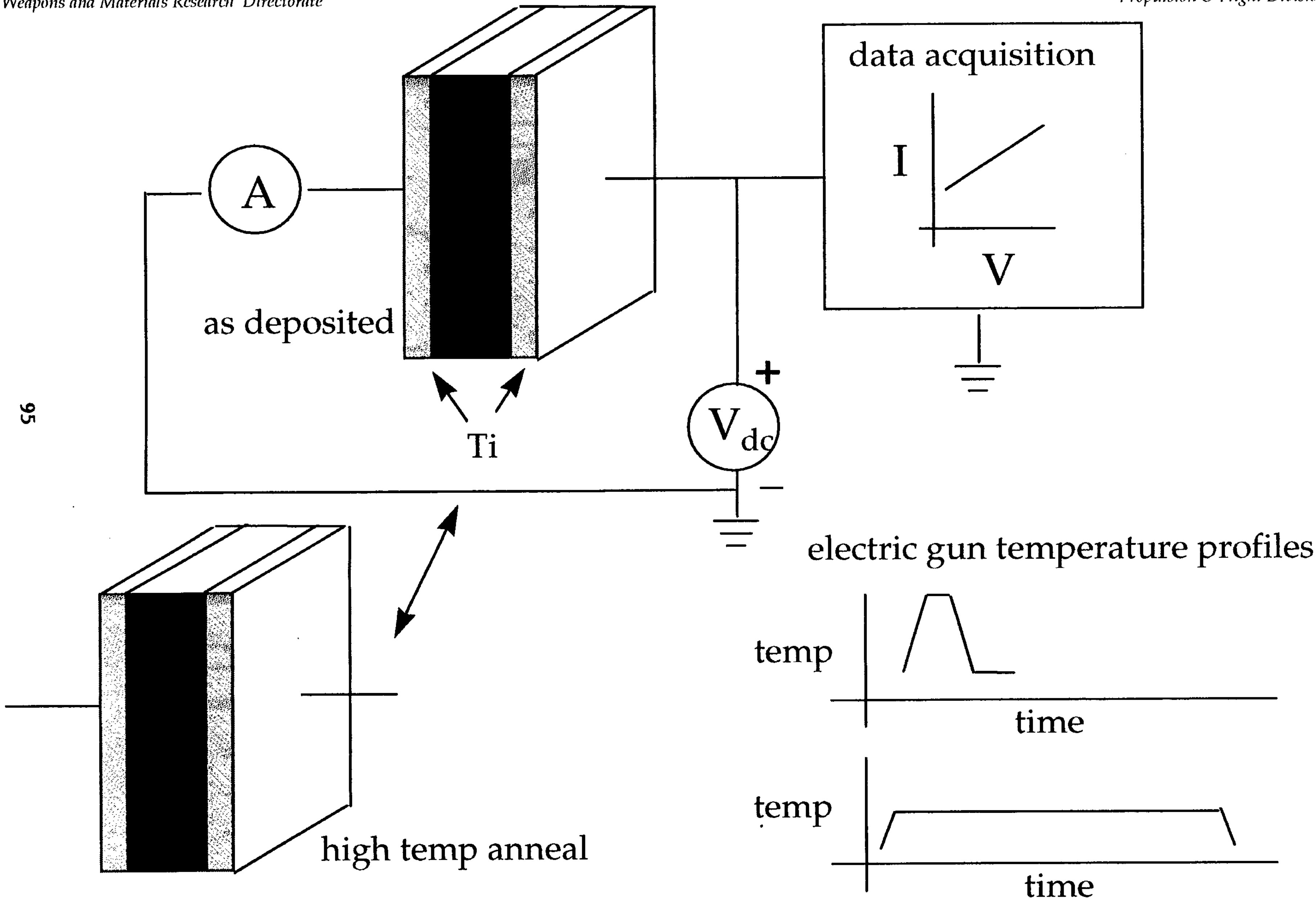
- Characterize electrical properties of the metal-SiC interface as a function of temperature
  - → focus on Ti-SiC and Ta-SiC
  - → characterize temperature effects on electrical transport properties using I-V measurement
    - rectifying vs ohmic contact
    - sample resistivity

Applications: pulsed power switch, ETC plasma generator components, EM rail material

Candidate metal contact materials for SiC

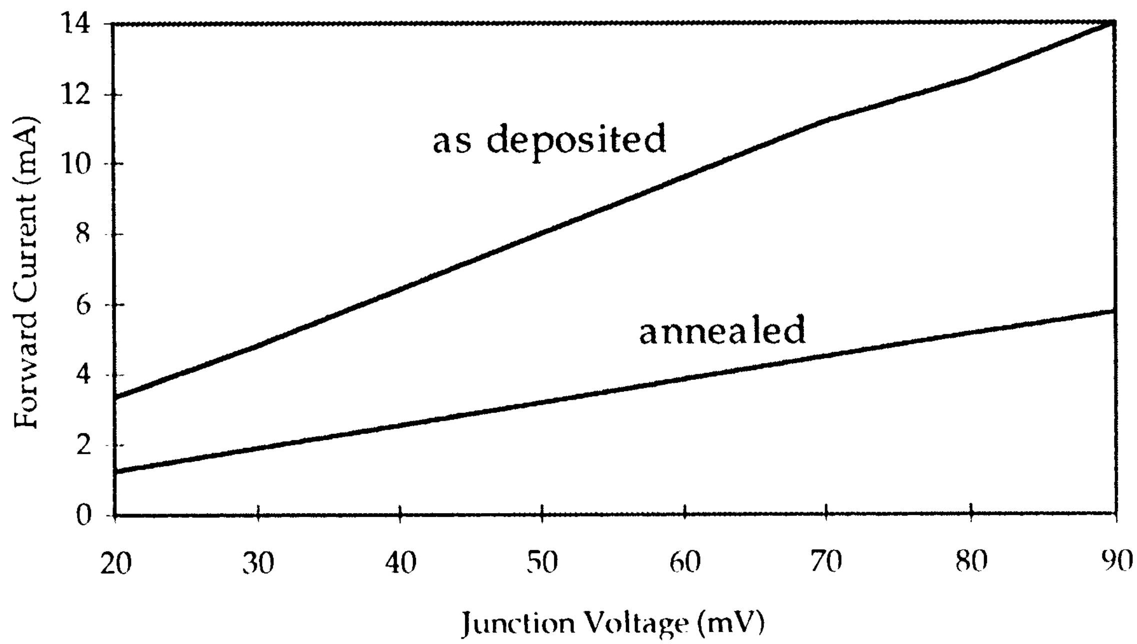
	melting temperature (degrees Celcius)	specific contact resistance (typical, ohms-cm^2)
✦ Al	660	1×10^{-5}
✦ Co	1495	
✦ Ni	1453	1×10^{-6}
✔ Ta	2996	
✔ Ti	1660	1×10^{-5}

I-V measurement apparatus



Ti-SiC I-V measurements

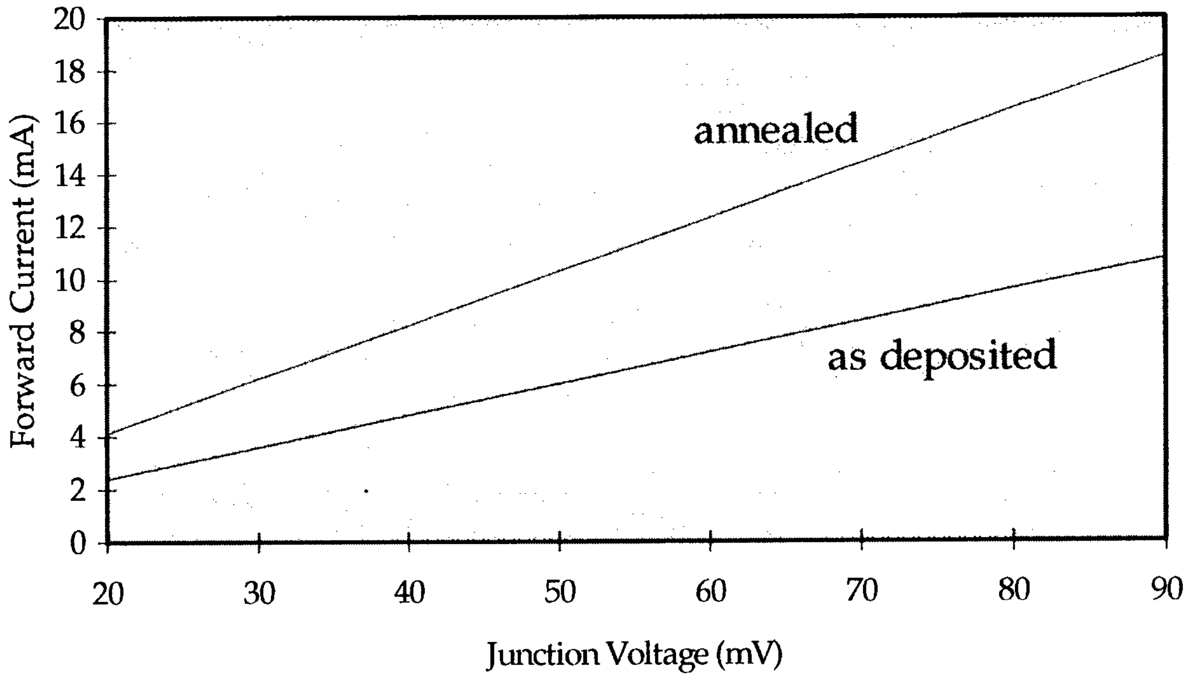
- Ti-SiC as deposited and annealed at 600 C, 5min



- formation of Ti-C, Ti-Si, Ti-O ?

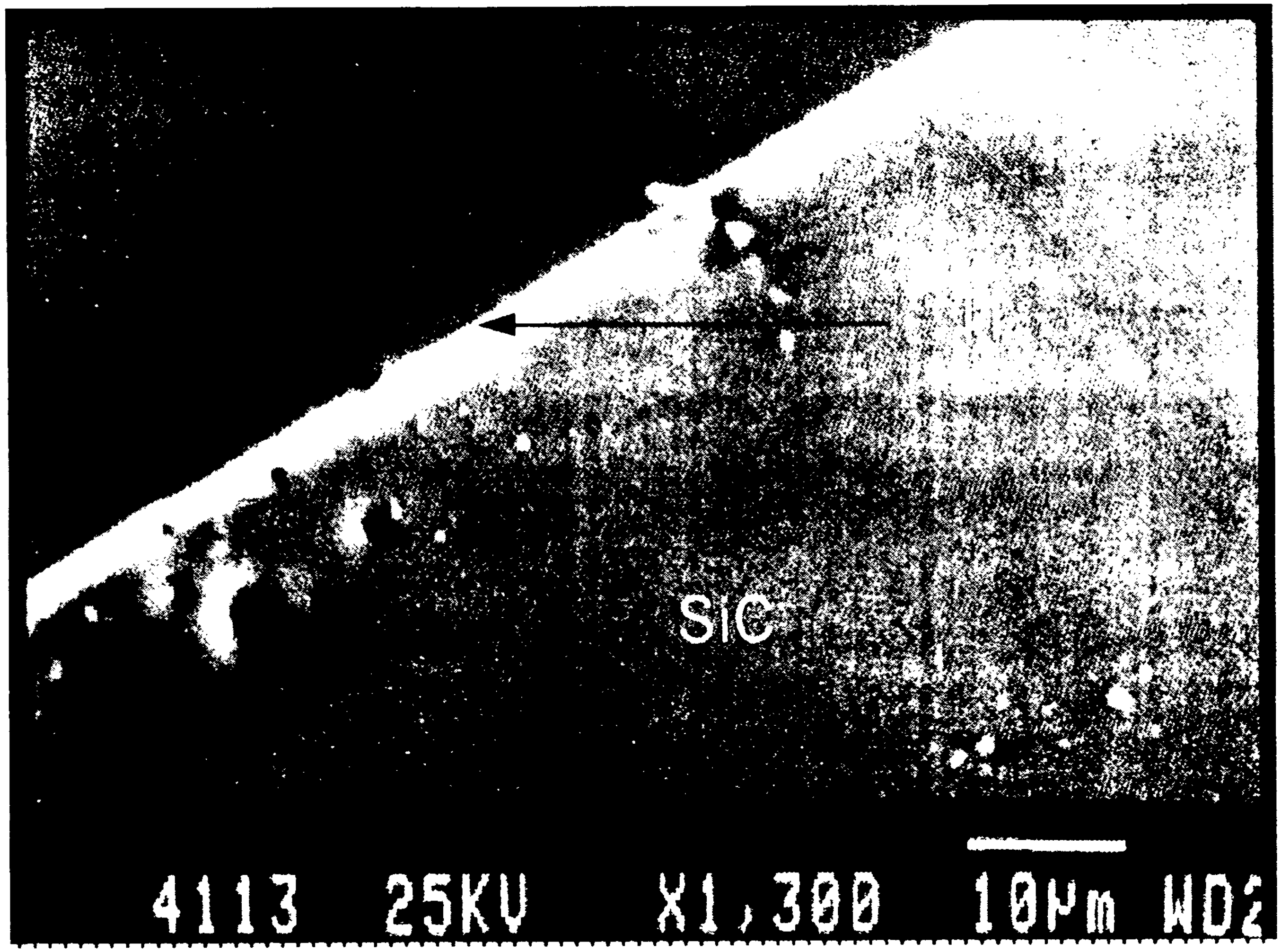
Ti-SiC I-V measurements

- Ti-SiC as deposited and annealed at 1120 C, 5min

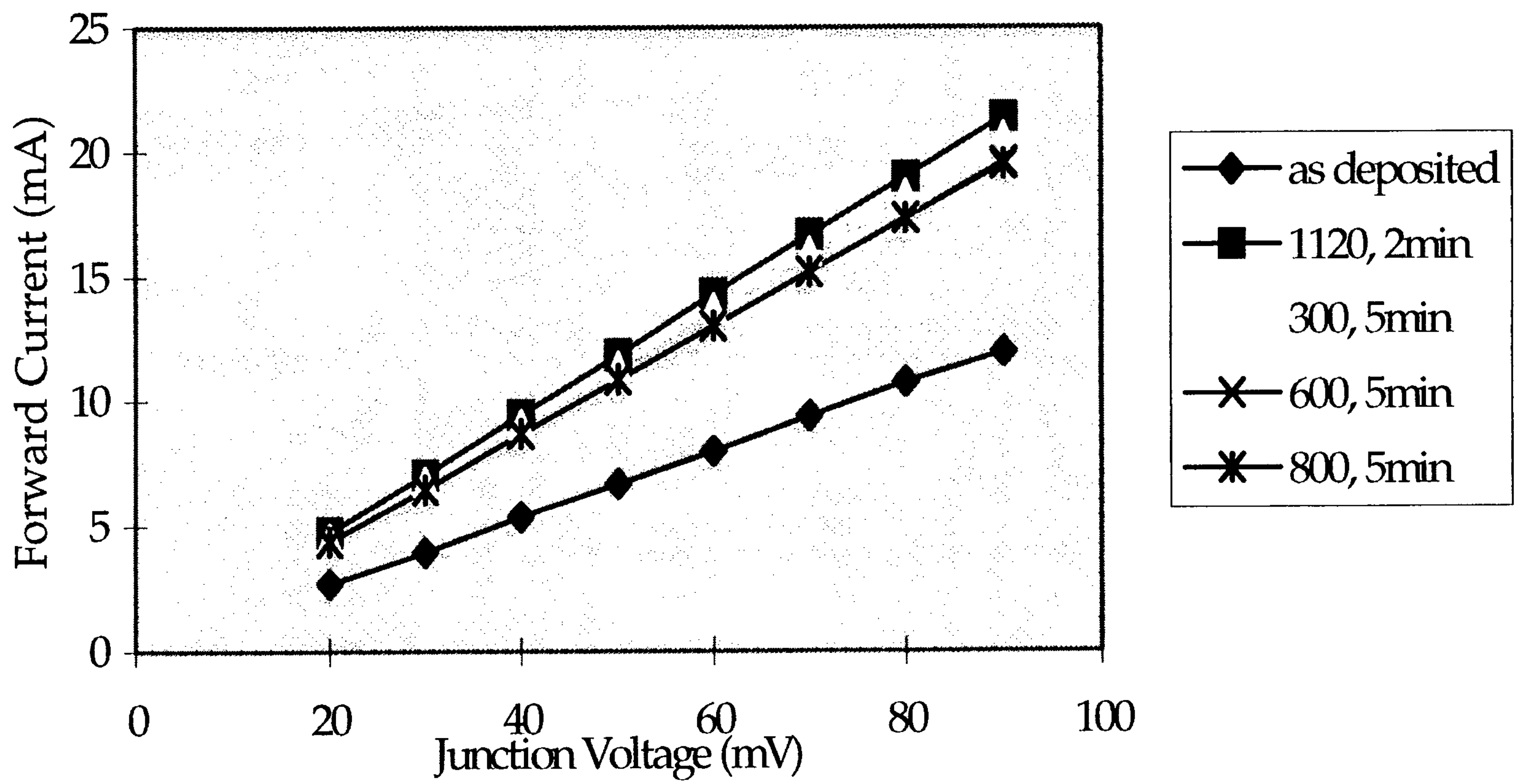


- Bell jar furnace replaced with rapid thermal annealer (RTA)

Ti-SiC interface



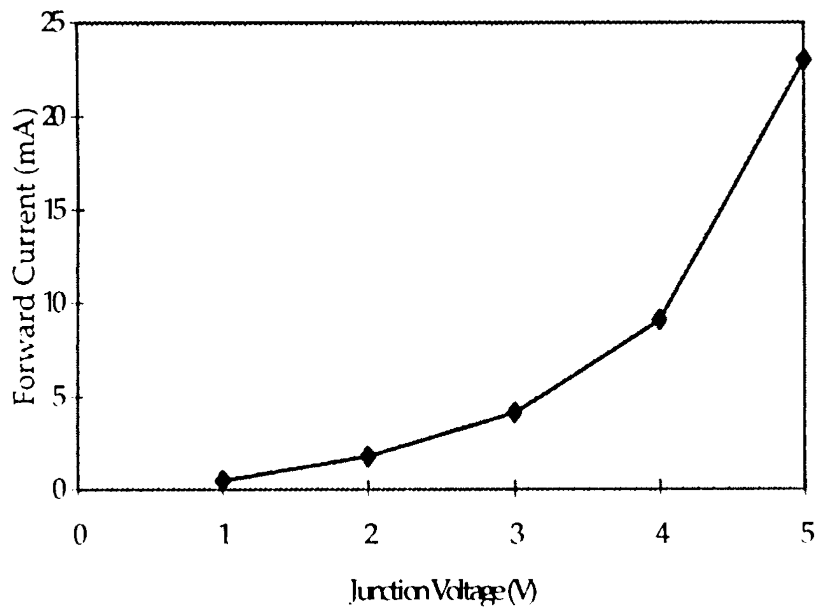
Ti-SiC I-V measurements



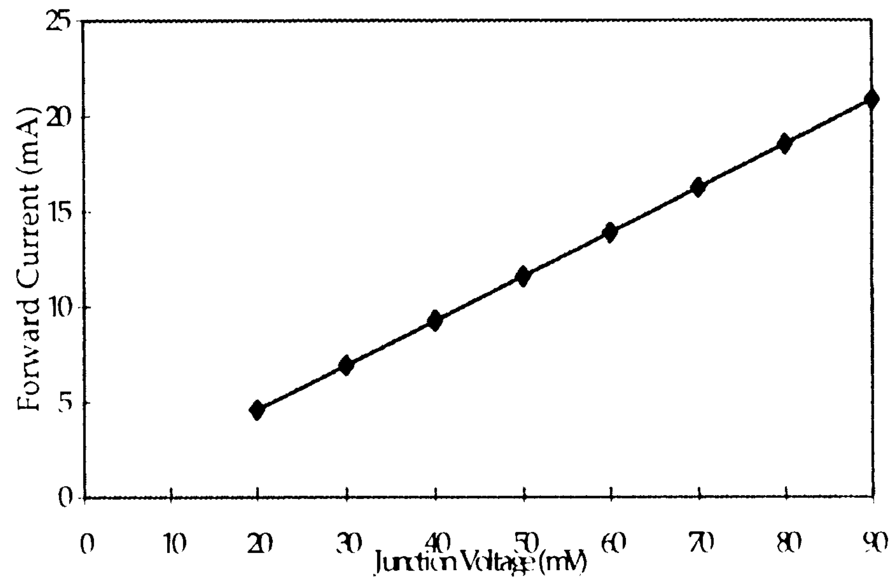
- Average resistance: 4.45 ohms
- Standard deviation: 0.167 ohms (3.8%)

Ta-SiC   I-V measurements

- Ta-SiC as deposited

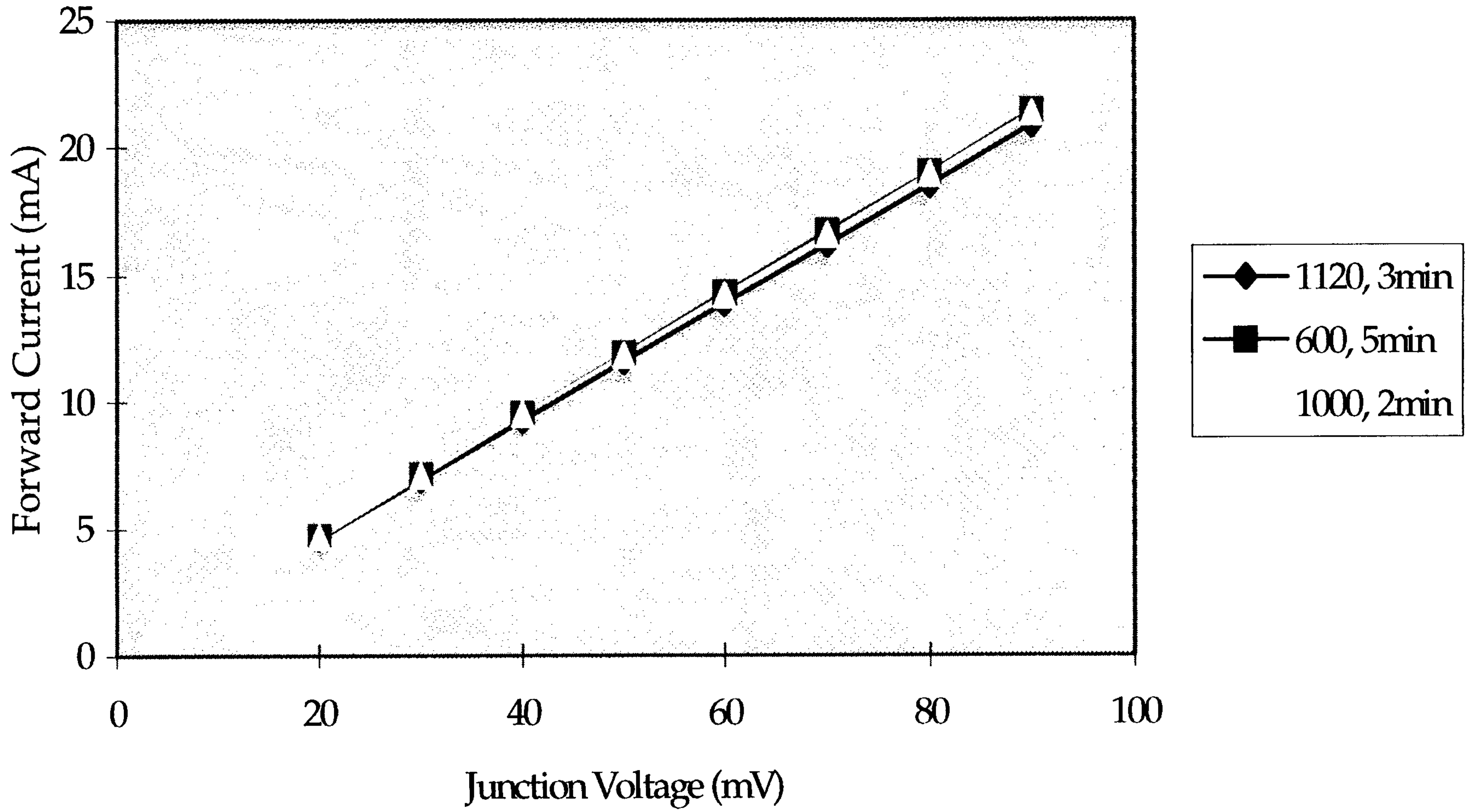


- Ta-SiC annealed 1120 C, 3min



- Difference in Ta work function could account for rectifying behavior

Ta-SiC I-V measurements

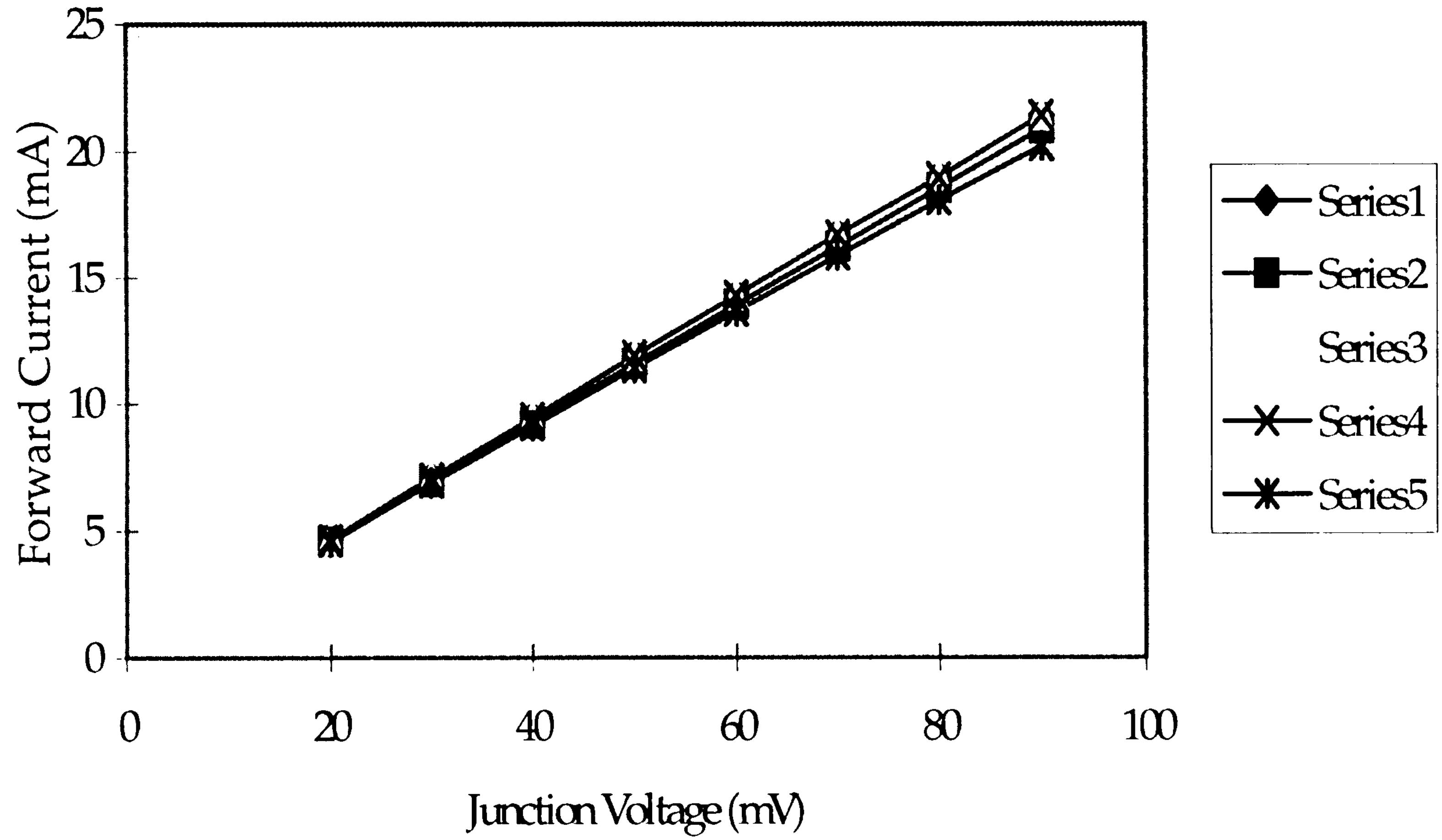


- Average resistance: 4.25 ohms
- Standard deviation: 0.05 ohms (1.2%)

I-V measurement reproducibility

Weapons and Materials Research Directorate

Propulsion & Flight Division



- Average resistance: 4.27 ohms
- Standard deviation: 0.07 ohms (1.7%)

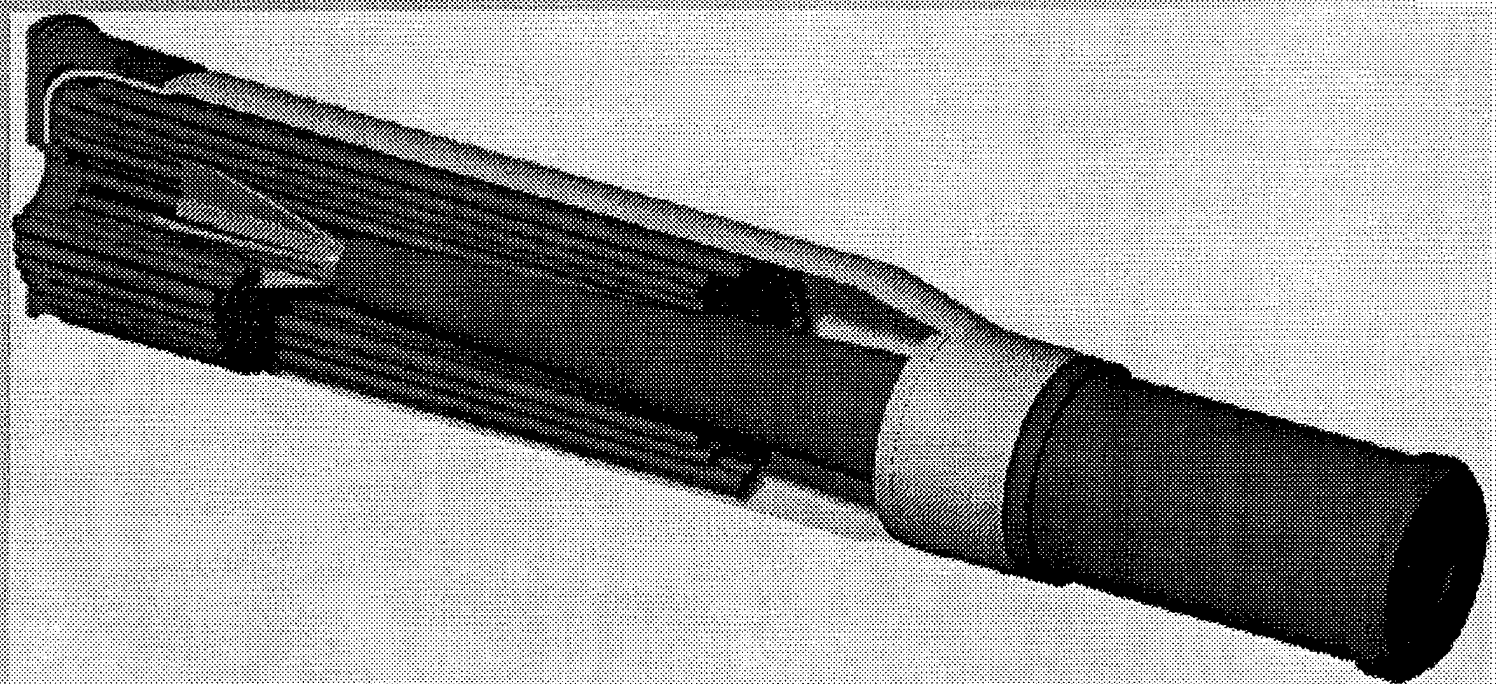
Summary

- Annealing process important for optomized electrical contact fabrication
- Ti-SiC demonstrated reliable electrical contact (s.d.=3.8%) in temperature range 300 - 1120 C
- Ta-SiC demonstrated reliable electrical contact (s.d.=1.2%) in temperature range 600 - 1120 C
- Futher long term temperature cycling recommended for continued electric gun materials analysis

Acknowledgments

- Dr. Steve Howard, ARL
- Dr. Paul Berger, UD
- Dr. Johnson Olowolafe, UD
- Ingolf Rau, UD

U.S. ETC Modeling Capabilities



Presented by G. Wren
on behalf of
U.S. ETC Modeling Team

to

U.S.-German DEA 1060
January 27, 1998
Aberdeen Proving Ground, MD

Outline

- Acknowledgements
- PFN
- Plasma
- Interior Ballistics
  - combustible cartridge case
  - plasma/propellant interaction
- Mechanical Response
  - propellant
  - projectile
- Summary

Acknowledgements

AHPCRC/ARL - S. Ray

ARL - M. Nusca, J. Powell, G. Wren

CRAFT Tech - A. Hosangadi, R. Sinha, S. Dash

NC State - J. Gilligan, M. Borham

PGA - P. Gough

SAIC - J. Batteh, C.C.-Hsaio, L. Thornhill, F. Su

UDLP - D. Cook

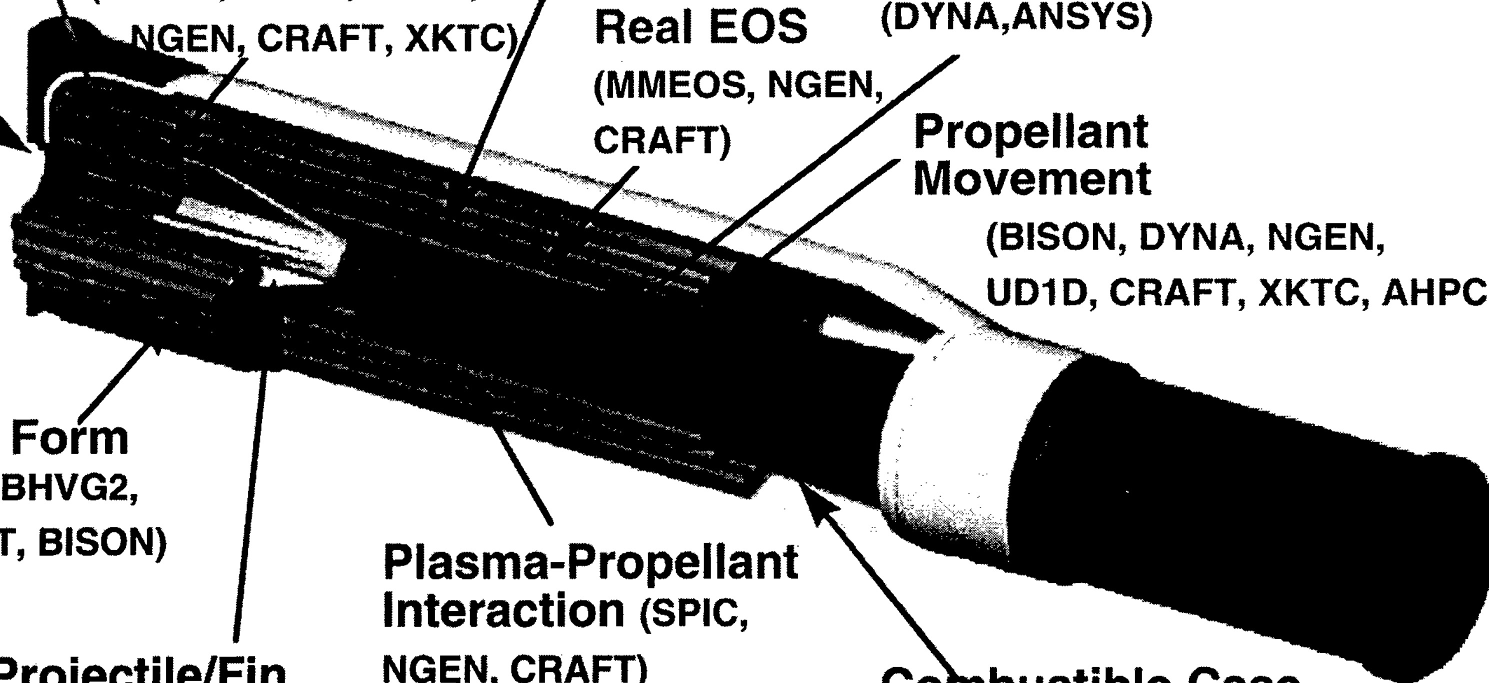
UT, Austin - D. Wilson

PFN Models

- ARL code, P2SIM
  - written by PCRL under contract to ARL
  - generalized PFN model
  - can be used for design
  - includes firing scenerios
  - linked to Plasma and IBHVG2 to form PPIB code
- SAIC code
  - PFNETC
  - SPICE
- UDLP code

DEFENSE SPECIAL WEAPONS AGENCY

Modeling Capabilities



PaulGoughAssoc

United Defense
FMC/BMY

CRAFTech

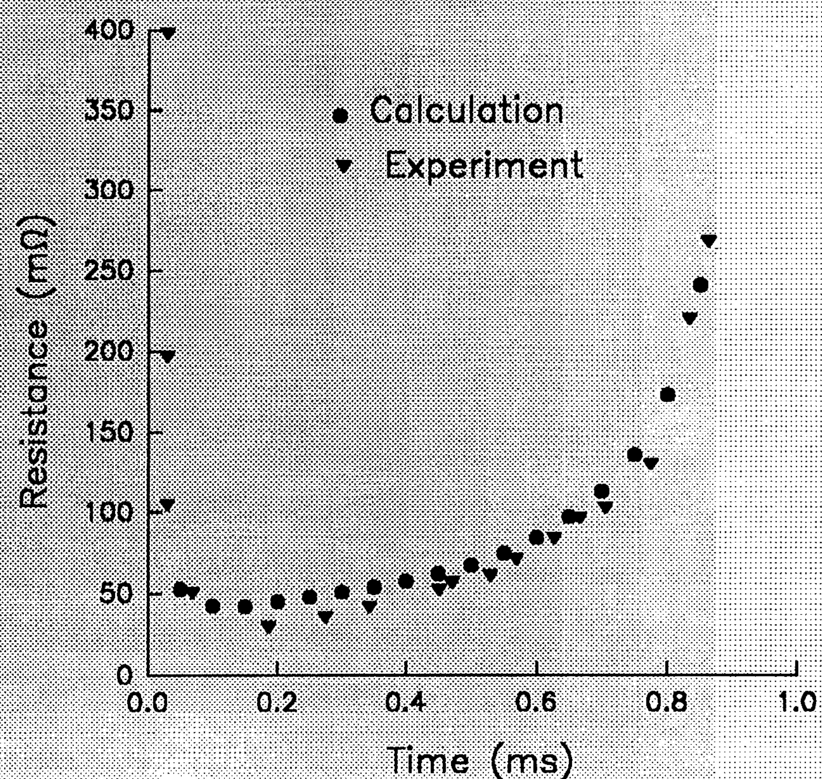
Plasma Models

- ARL/SAIC
  - generalized, rear plasma capillary model
  - models of experimental devices for coupling to IB codes
  - detailed models to investigate plasma physics
- NC State
  - effects of vapor shielding
  - boundary layers, effects of radiation and turbulence on energy transport
- UDLP
  - characterization of plasma properties as function of injector geometry and power-supply characteristics
  - correlation of theory and experiment
- UT, Austin
  - characterization of plasma expansion
  - theoretical model development
  - correlation of theory and fundamental experiments

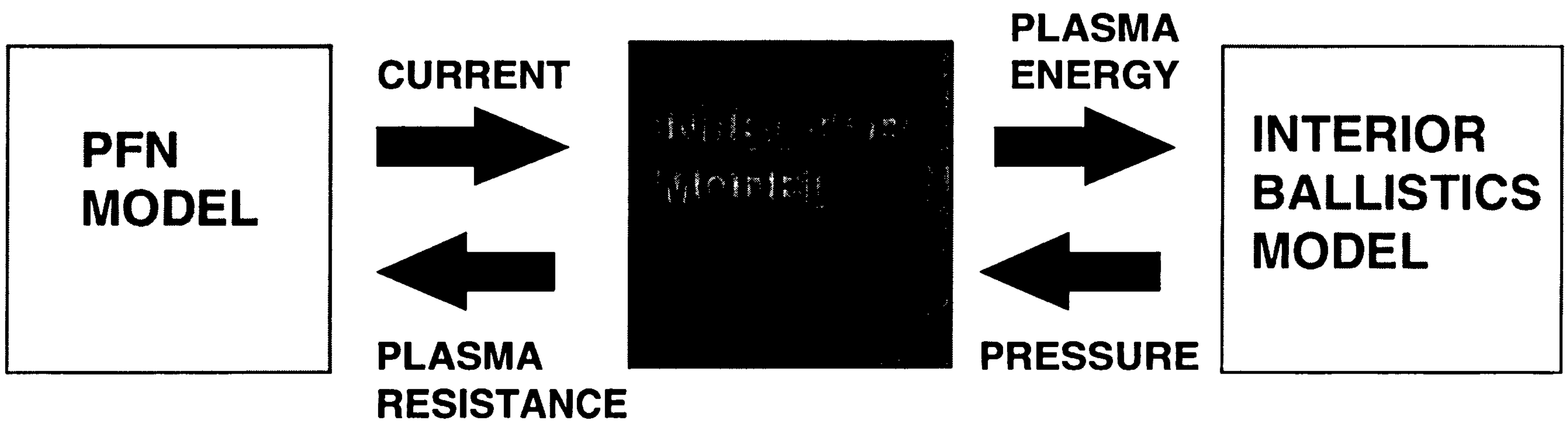
ARL Generic Plasma Model

- One-dimensional
- Transient
- Nonideal plasma properties
- Arbitrary mixture of species
- No adjustable parameters
- Application to various injector designs
  - breech
  - piccolo
  - extender tube
- Simplified version of model
  - isothermal
  - quasi-static

Comparison of Theory with ISL Experimental Data



UDLP End-to-end Engineering Model



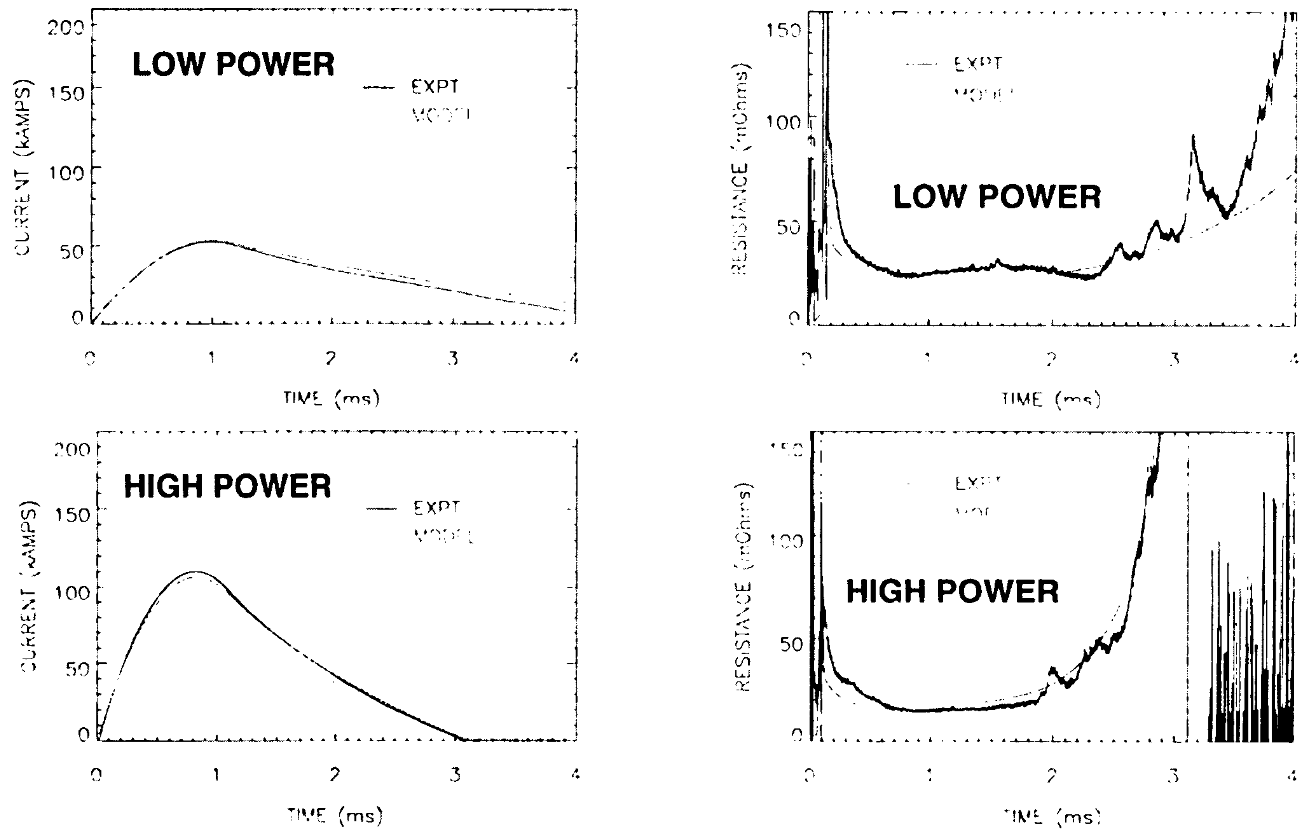
- Fully coupled modules (single executable). Typical applications:
  - Injector design trade studies and fault analysis
  - Cartridge integration analysis
  - System studies

- Gaps in physics models exist (i.e. plasma/propellant interaction). Calibrated empirical model used until more fundamental data available.

Injector Model Features

- Independent injectors in series and/or parallel.
- Resolve injector large holes or use average porosity for smaller holes. Independently coupled to interior ballistics routine. Adiabatic radial flow.
- Ionized species H^+, C^+, Cu^+, Cu^{++}. Ablation from walls via blackbody radiation. Ablation from electrodes proportional to action.
- Adapted Spitzer plasma resistivity model
- Thermodynamics calibrated with existing models

Full Scale Direct Fire Electrical Data



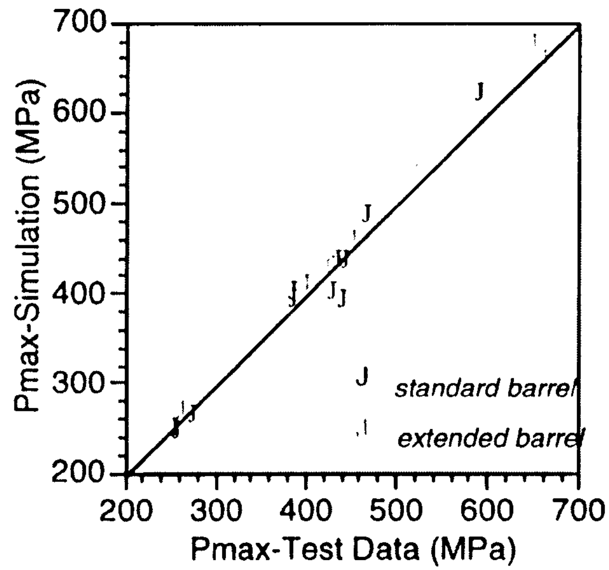
Injector model calibrated against large ETC database

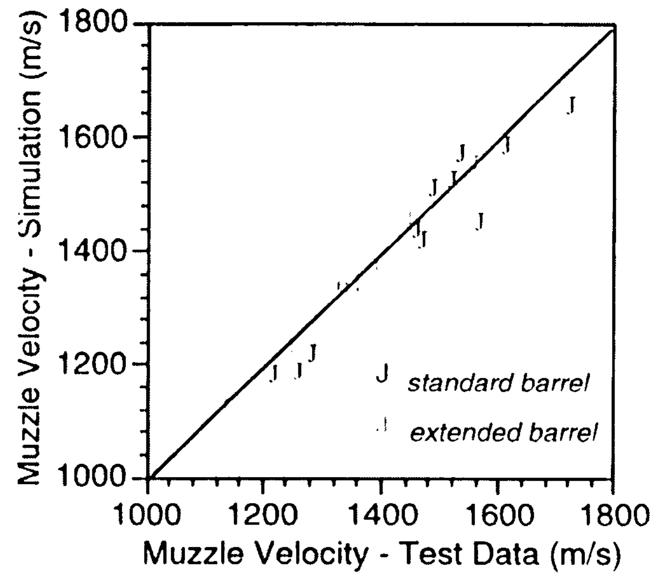
Interior Ballistics

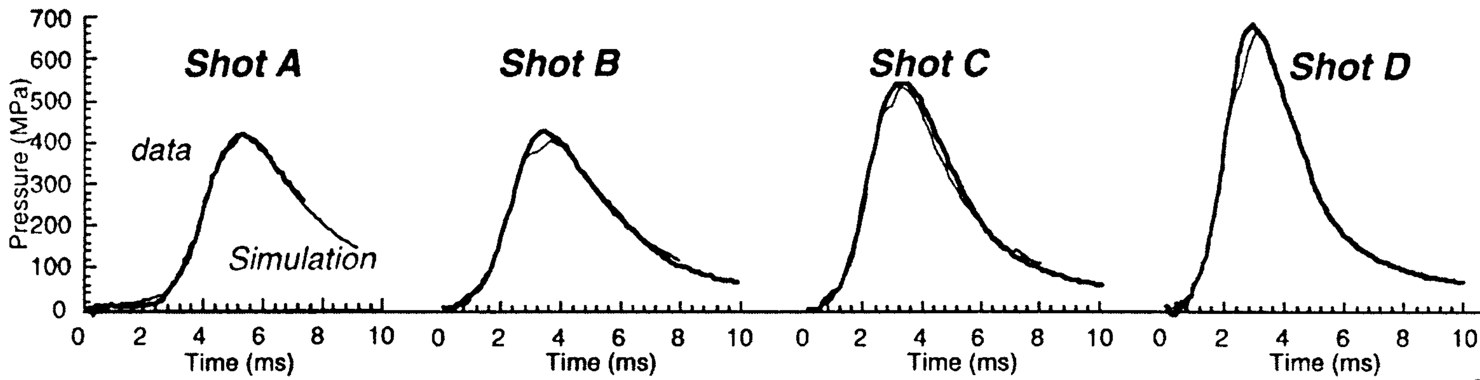
- Fully coupled, fluid/structure interaction of plasma/propellant
  - AHPCRC at University of Minnesota
  - finite element models of fluid provide high fidelity
- Zero and one-dimensional models for experimental firings
  - IBHVG2, UDLP, XKTC
- Generalized, multi-phase, multi-dimensional codes
  - BISON, CRAFT, NGEN
  - calculations in conjunction with fundamental diagnostics
  - plasma/propellant interaction
  - support for experimental design
- Special codes to investigate specific phenomena
  - characterization of plasma properties
  - structural response of propellant or projectile
  - thermal response/erosion of projectile fins
  - thermochemistry of plasma/propellant

DEFENSE SPECIAL WEAPONS AGENCY

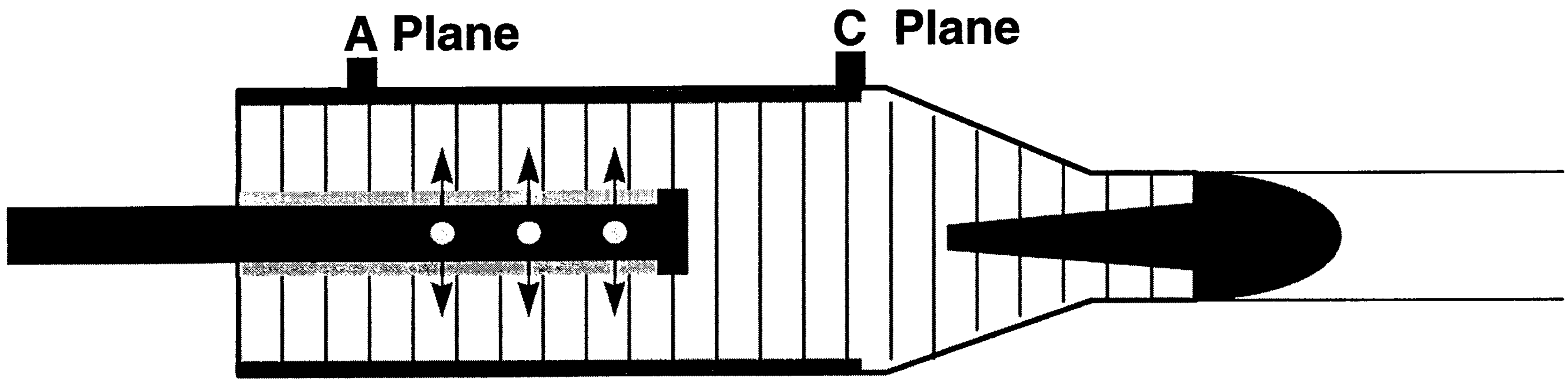
Modeling Tools Have Been Validated Against Experimental Data







Interior Ballistics Computational Domain

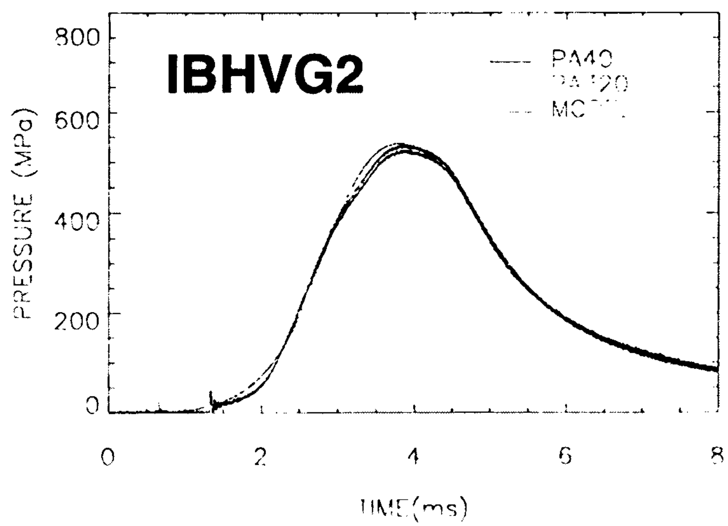


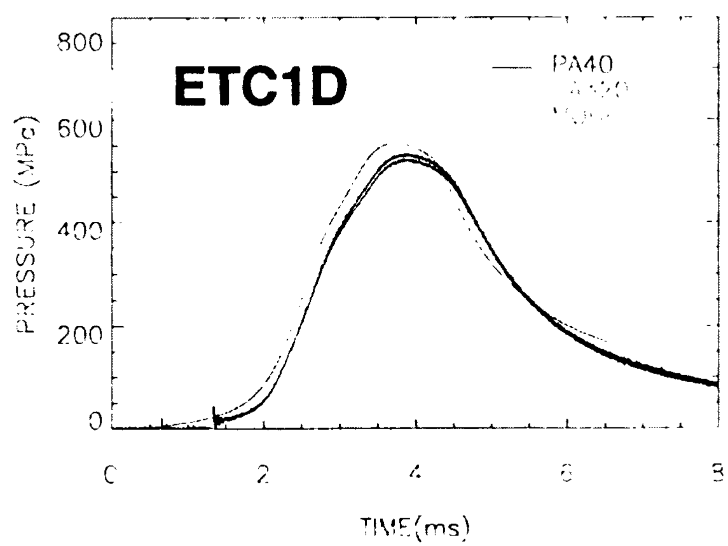
Variable area multi-phase 1-D model including:

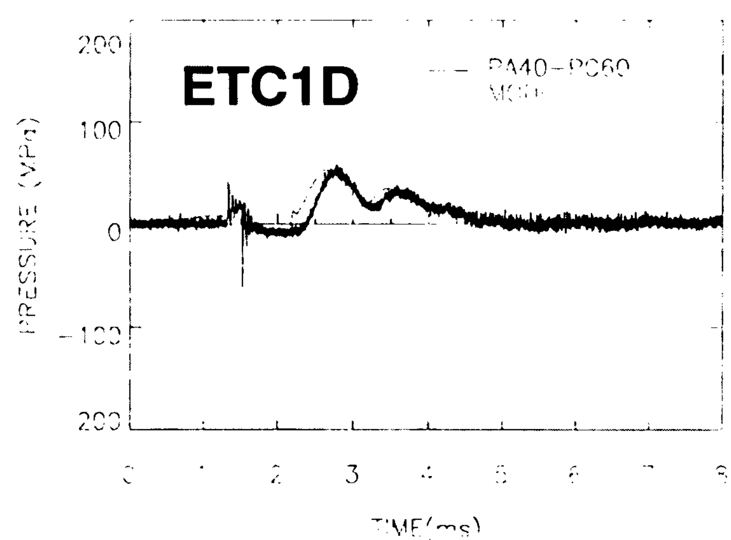
- grid expansion with projectile motion (number of cells constant)
- flexible injector position and design
- chambrage and variable area projectile tail boom
- propellant bed compressibility and stress propagation
- grain motion and splintering
- cartridge case combustion

Low Power Data

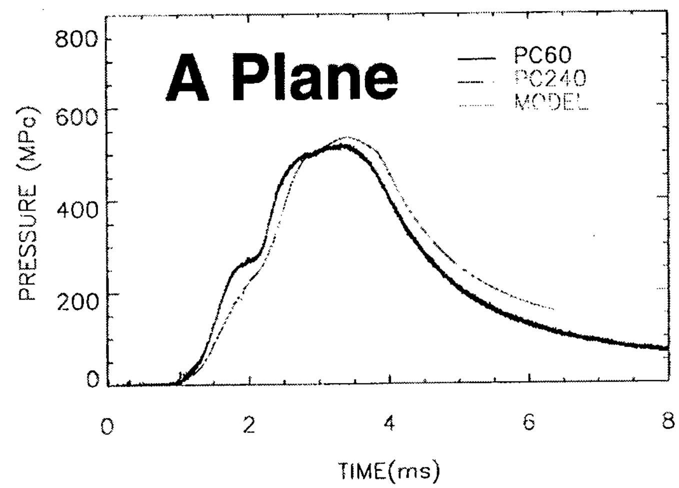
- Standard lumped parameter codes support pre-test analysis and charge design. Post-fire 1-D analysis typically performed when waves are observed.

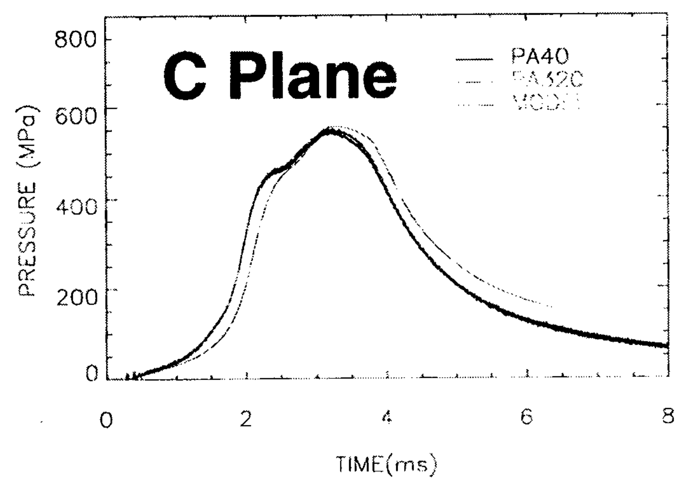


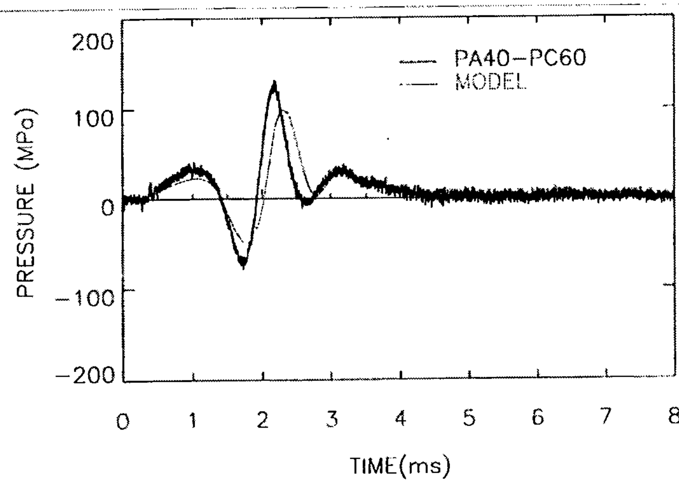




High Power Data ETC1D Calculation



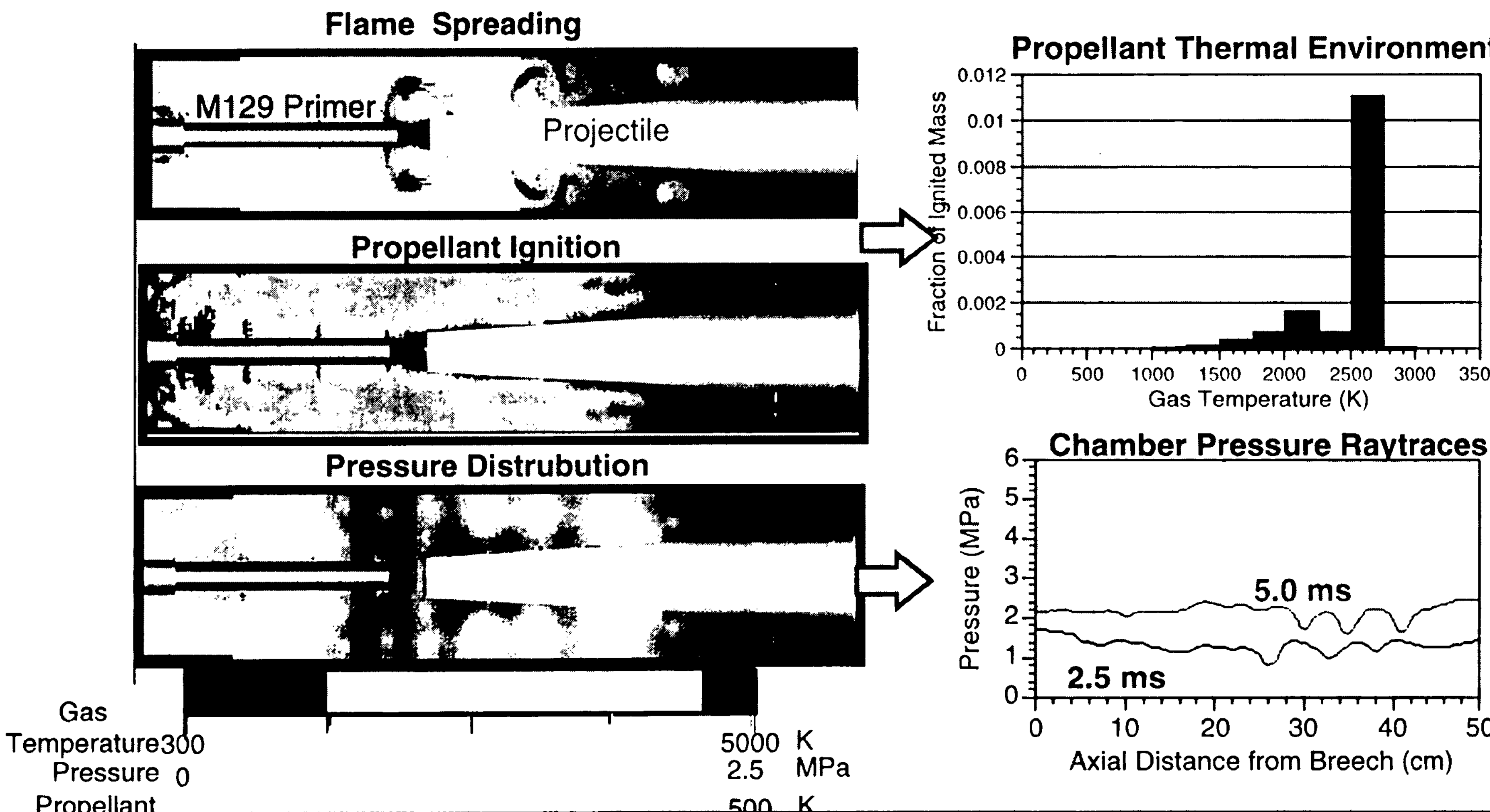




- **Calculations not shifted in time**
- **Combustion driven by pressure from initial plasma injection**

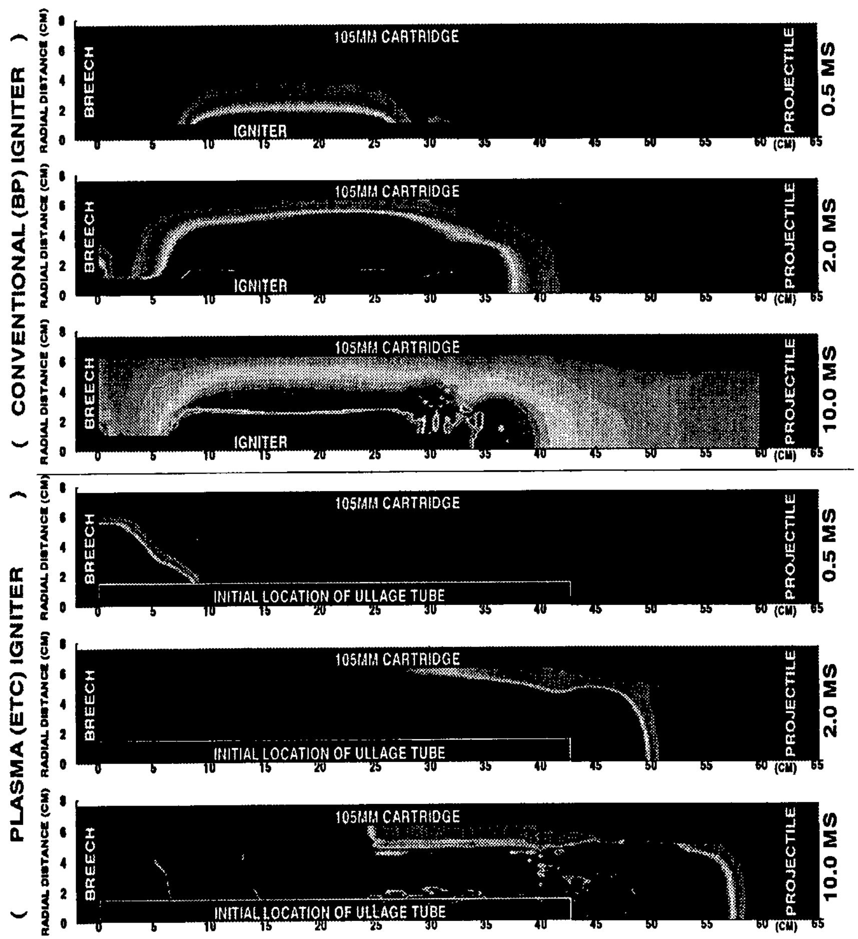
DEFENSE SPECIAL WEAPONS AGENCY

Modeling Is Used to Understand M829A2 Conventional Ignition



Computational Fluid Dynamics (CFD) Simulation for ETC Ignition of SP

Dr. M.J. Nusca, ARL-WMRD-PFD



- Simulation of a 105mm cartridge test firing at SOREQ.
- M30 and inert polymer grains.
- Centercore black powder (42 g) igniter (4ms duration).
- ETC (120MW peak power) igniter with centercore tube (1.5ms duration).
- Flowfield computations from NGEN code (ARL) excluding radiation heating of propellant.
- Red indicates Tgrain > Tign.

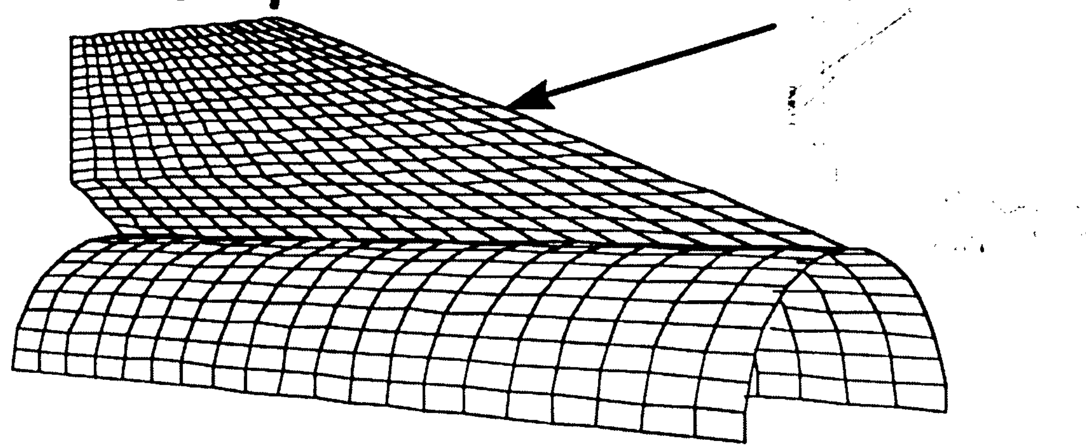
(Propulsion Physics Workpackage)

(Nusca, ARL, 1/98)

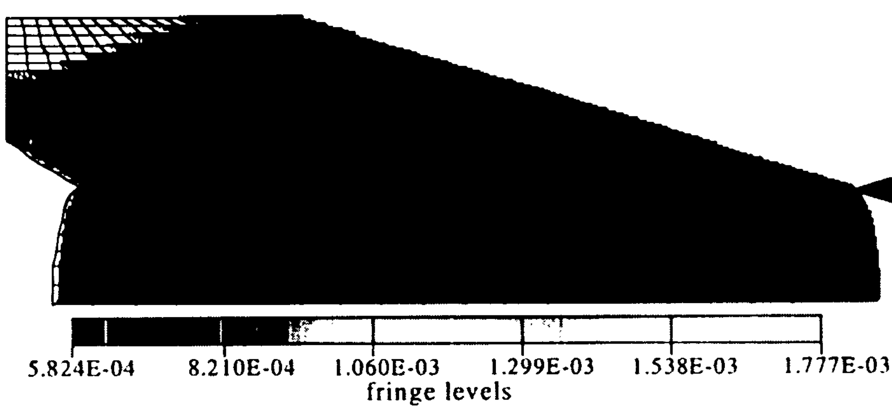
DEFENSE SPECIAL WEAPONS AGENCY

Modeling Analyzed Fin Response to Unbalanced Pressure Loading

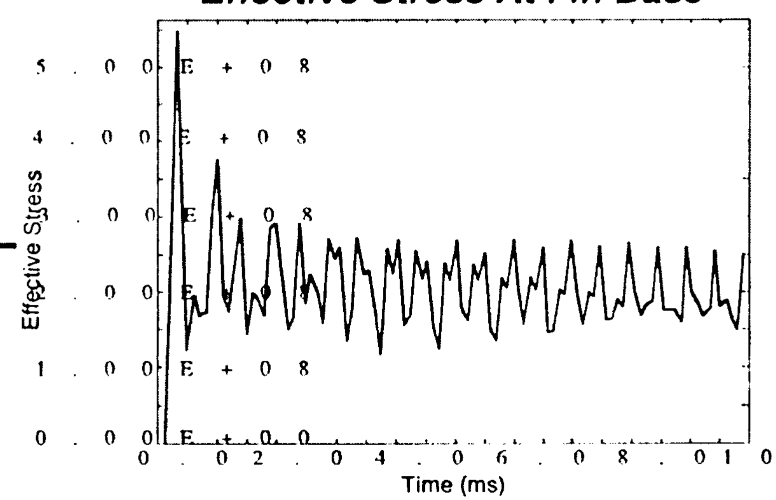
Computational Grid



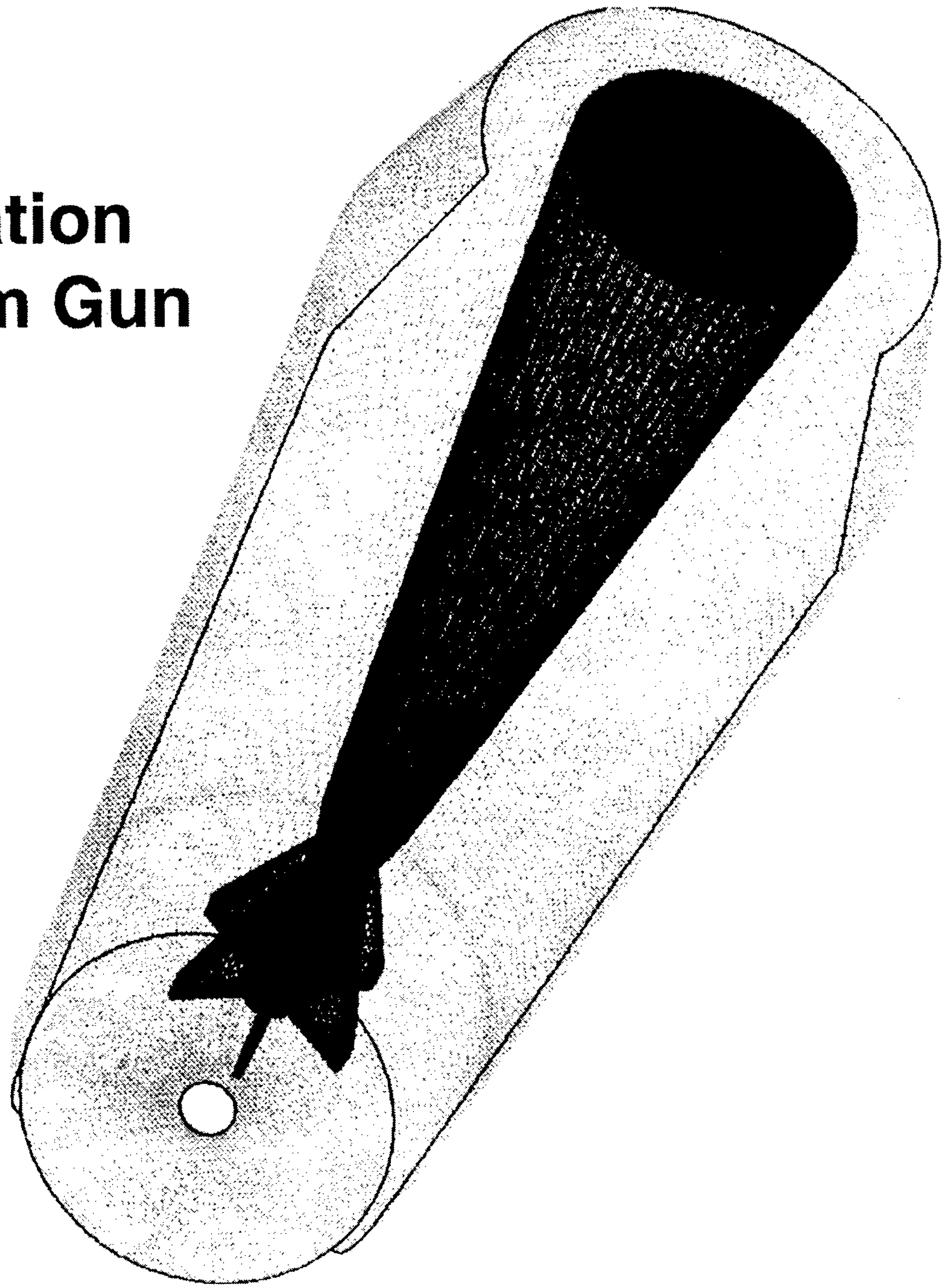
Strain Contours



Effective Stress At Fin Base



3D Simulation of 120mm Gun

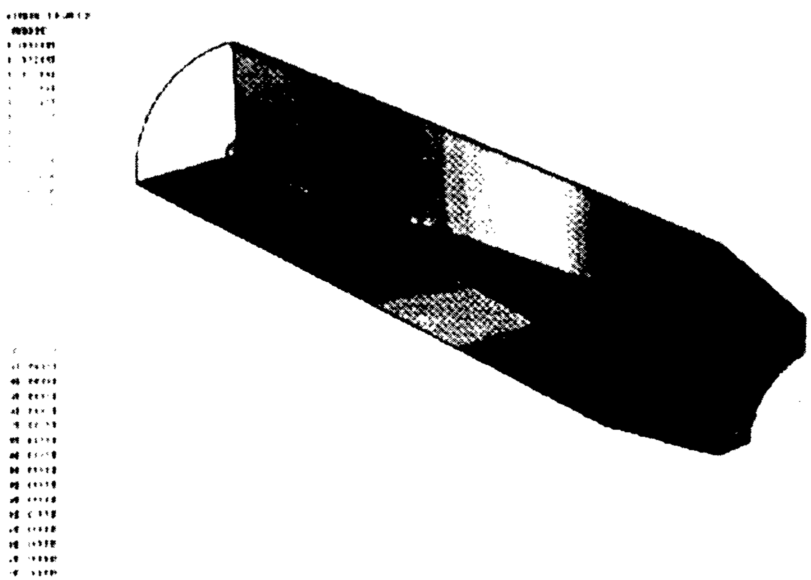


CRAFT code

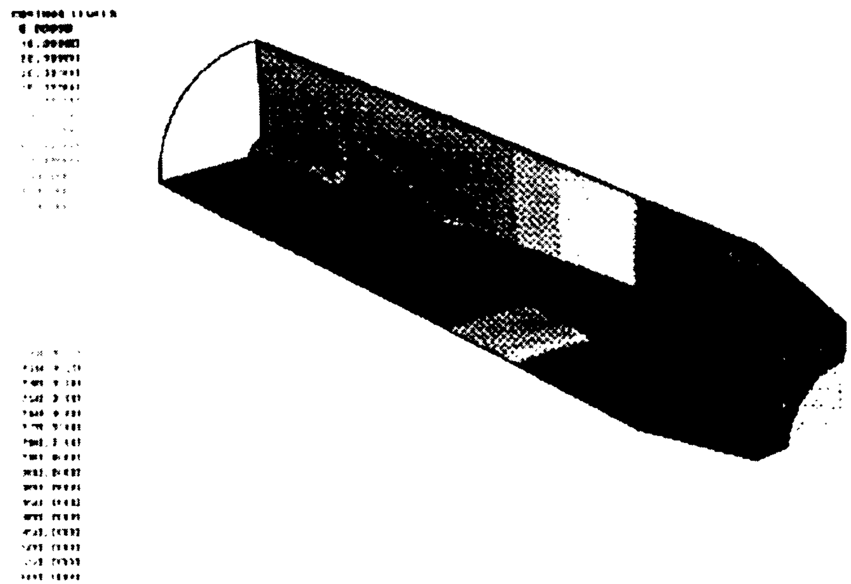
CRAFTech

Simulation of Pressure Waves in 120mm Gun

1.2 ms



1.3 ms



CRAFT code

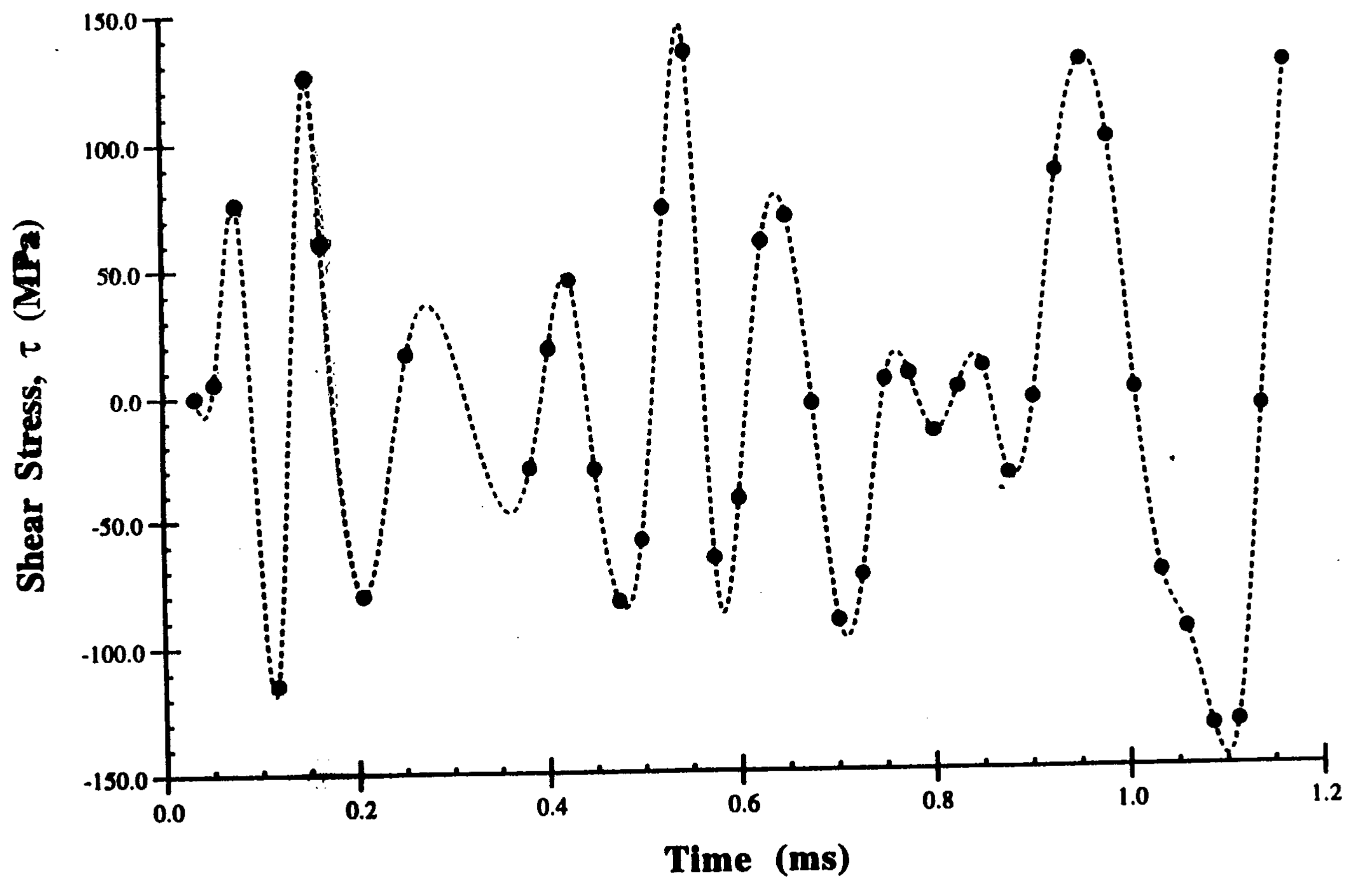
CRAFTech

Projectile Separation

CRAFT Technology

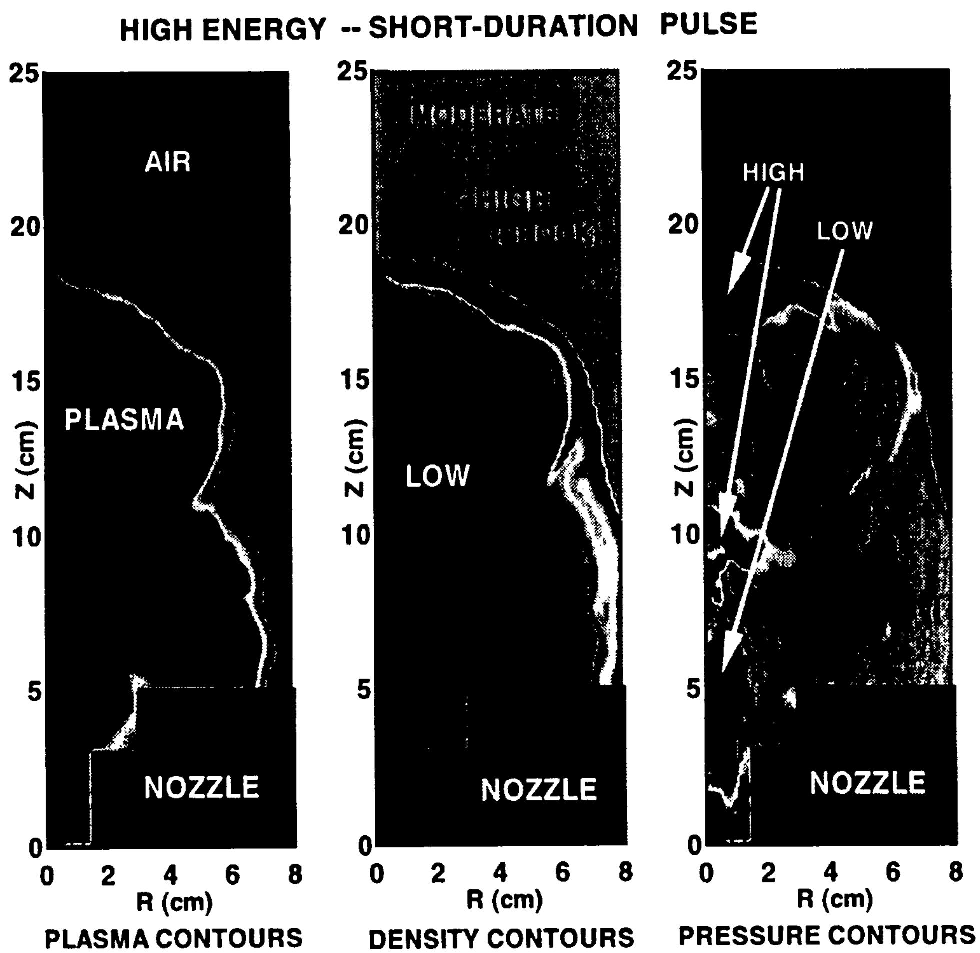
Propulsion & Flight Division

Calculated Shear Stress at Projectile/Fin Junction



Computational Fluid Dynamics (CFD) Simulation of an Open-Air Plasma Jet

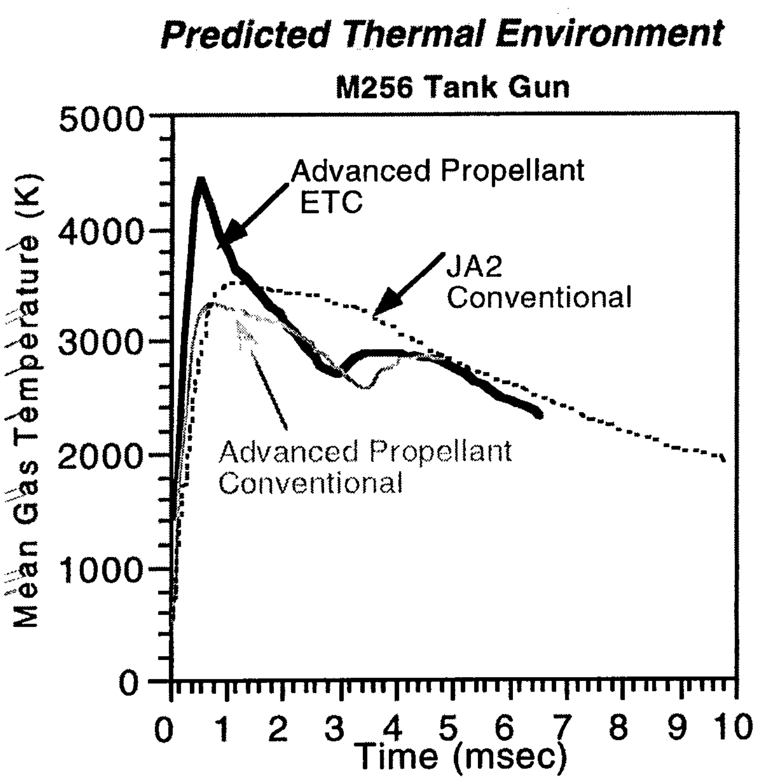
Dr. M.J. Nusca, ARL-WMRD-PFD

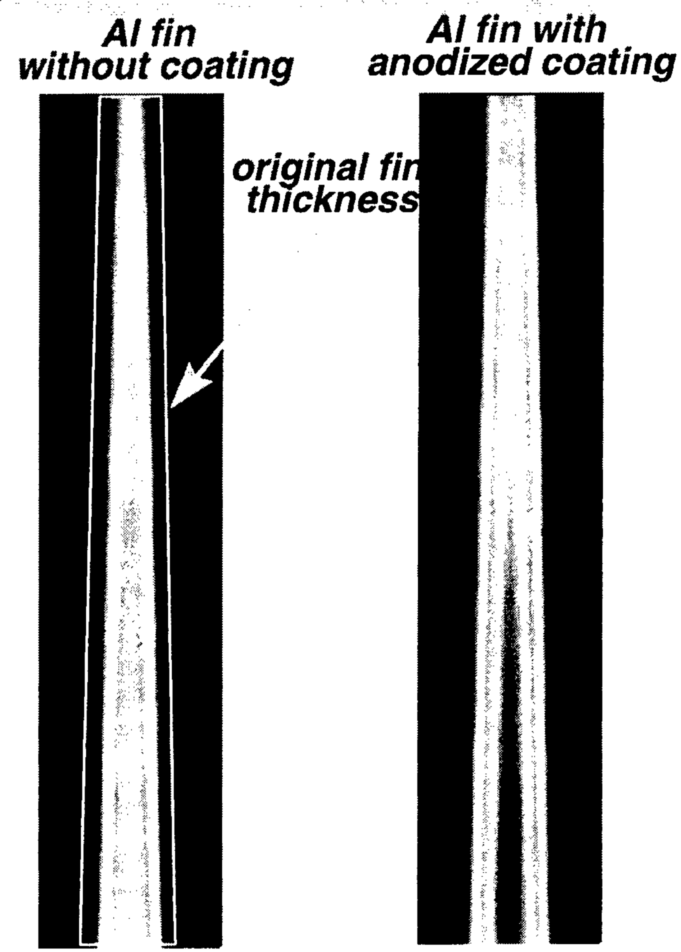


- Simulation of an open-air test series by Dr. K. White, ARL.
- PFN: 38kJ over .55ms (150MW and 50kA peak values).
- Plasma density, temp., velocity, etc., at nozzle inlet, from Dr. J. Powell's code (ARL).
- Plasma jet flow simulated by Nusca using the FAST3D code.
- FAST3D code (NRL) is a test CFD code for FCT algorithm in ARL's NGEN code.
- Joint ARL-NRL HPC (high-performance computing) effort.

(Nusca, ARL, 1/98)

Modeling Is Used to Analyze Fin Erosion





Summary

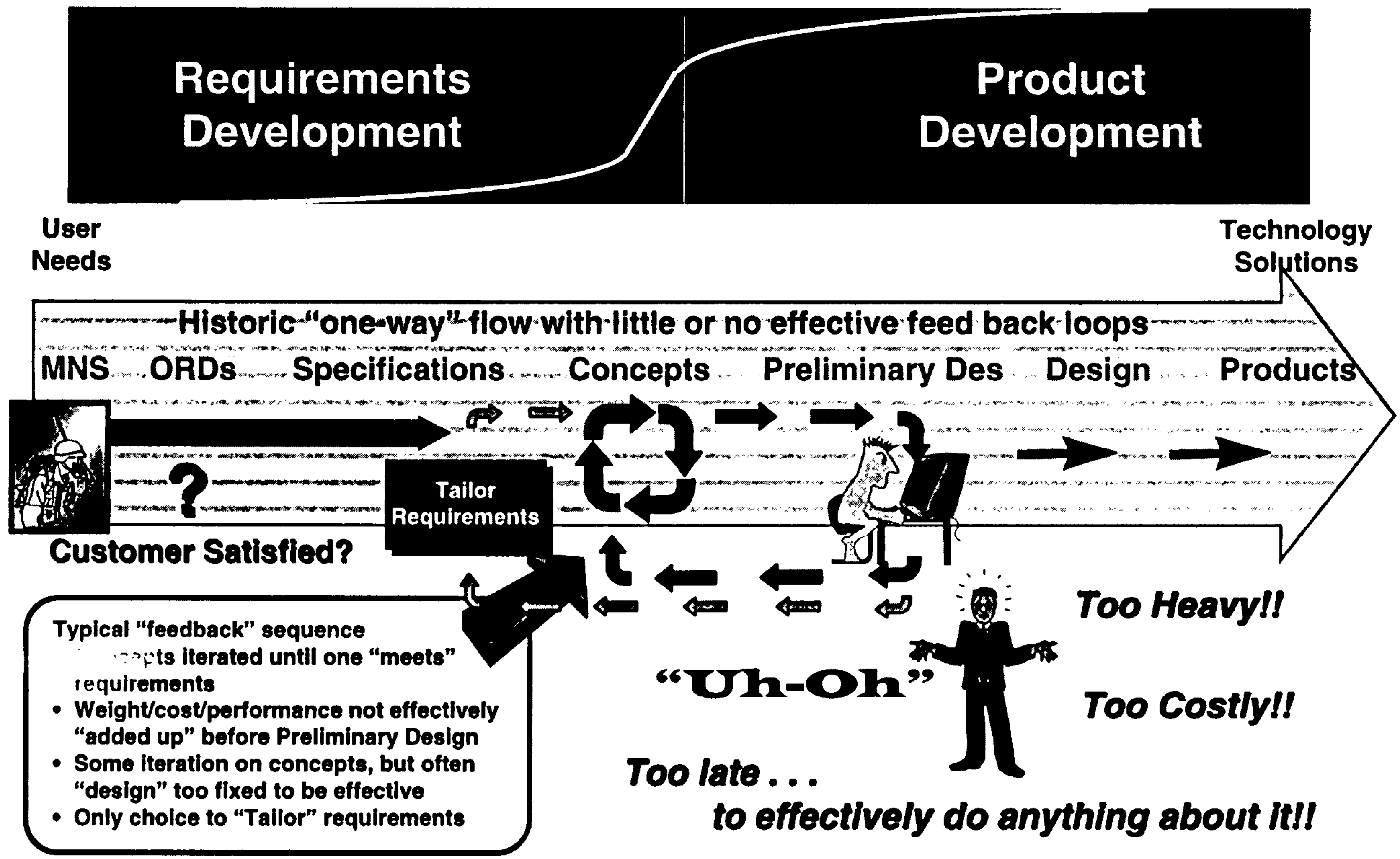
- Full range of ETC modeling
  - PFN, Plasma, Interior Ballistics
  - Zero, one, two and three-dimensional codes
- Efforts at various locations support each other
  - talented group of researchers
  - allows investigation of fundamental physics while supporting experimental design
  - leads to understanding of controlling physics
- Current focus on plasma/propellant interaction
  - closely tied to diagnostic efforts
  - characterization of plasma, the propellant, and the interaction
- Talented group of researchers
  - challenge is to keep pace with evolution of design and propellants

Advanced Armament System Development & Weaponization

Presented
to
DEA-G-1060
German/US Workshop
at
Armaments Research Laboratory
Aberdeen Proving Grounds
Aberdeen MD, USA

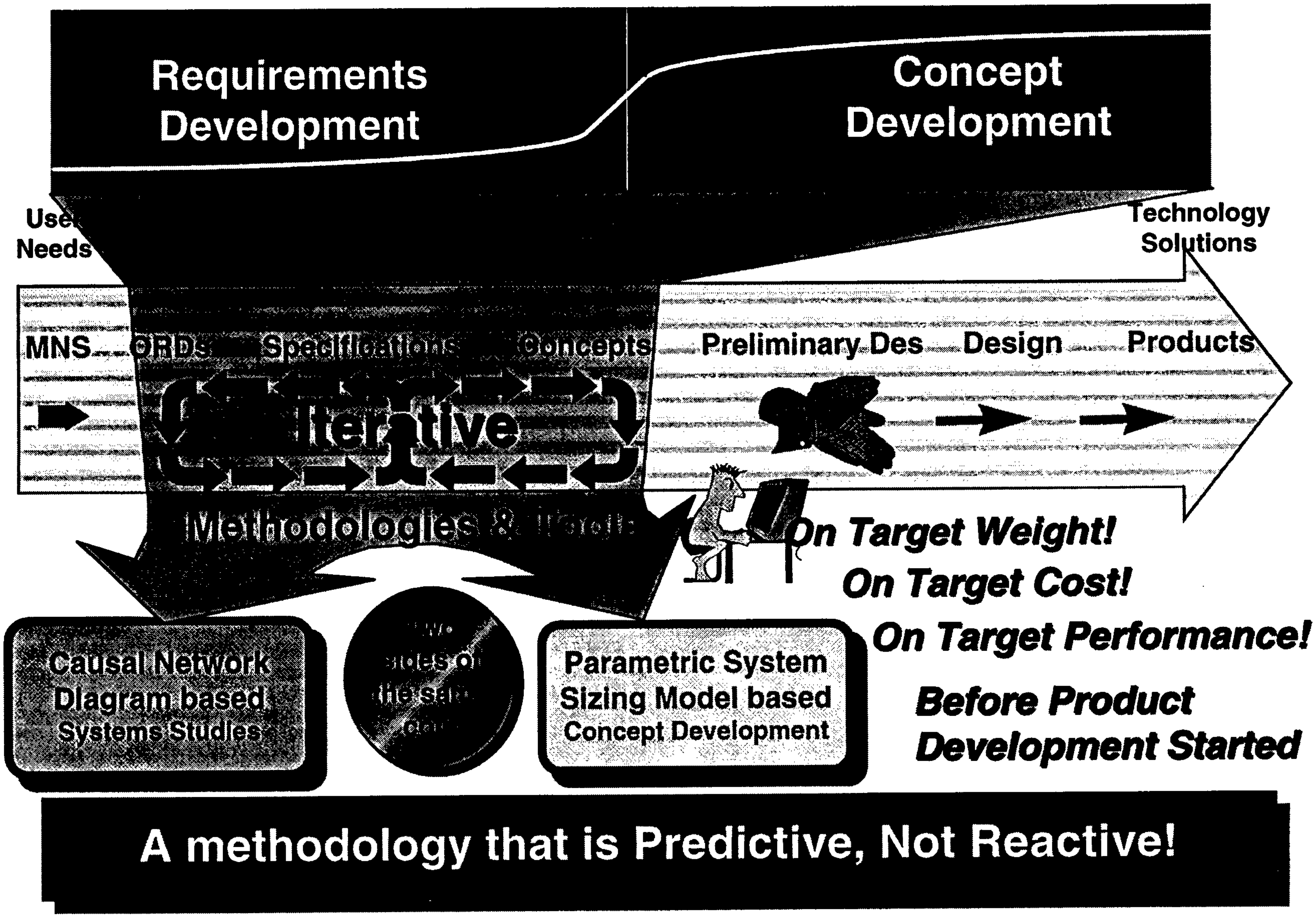
January 27-28, 1998

Historic System Development



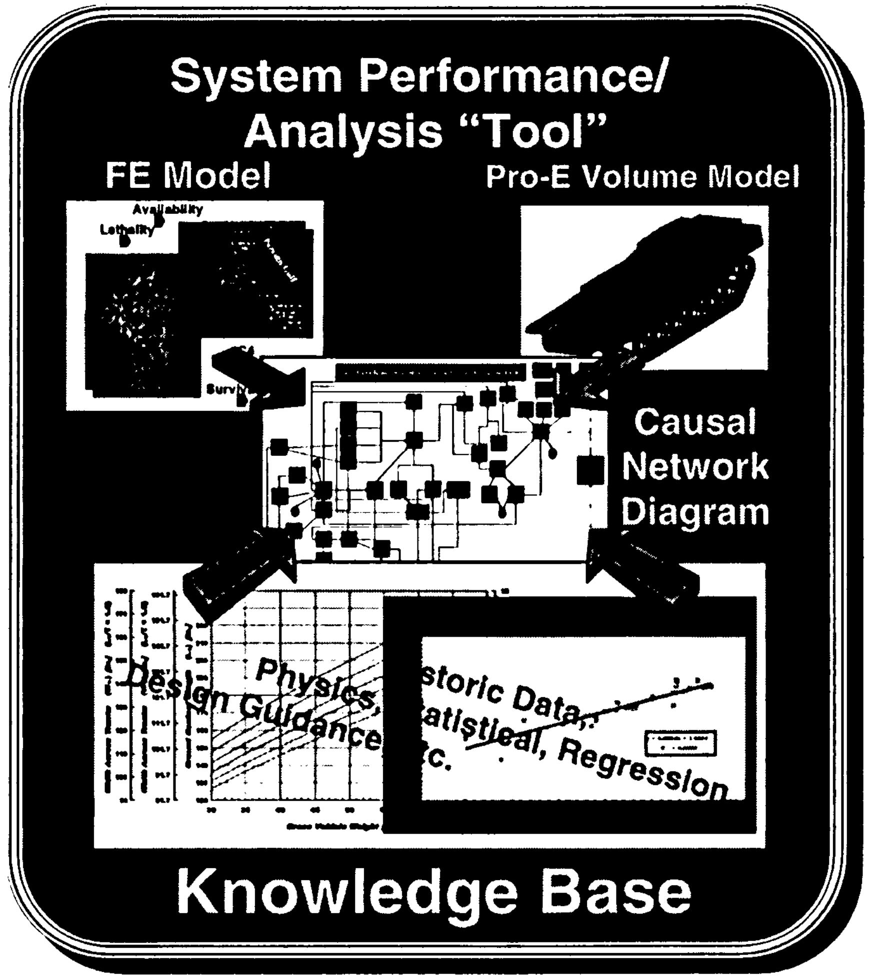
Typically it has been "bottoms-up" AND *Reactive*

System Development "Continuum"



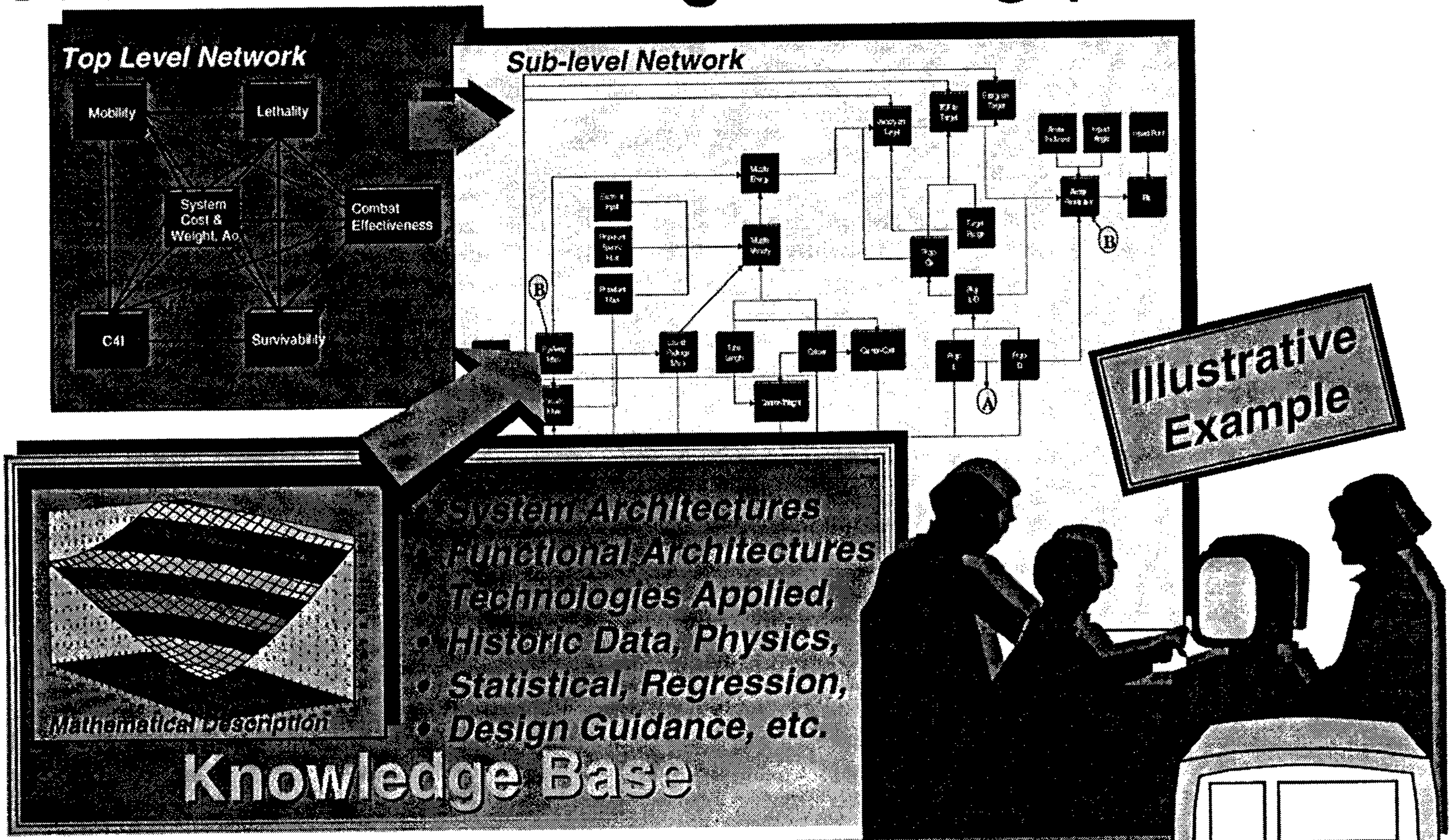
System Development Tools Objectives

- Provides rapid means to:
  - –Evaluate System/Subsystem (S/S) Performance in Terms of Combat/Force Effectiveness
  - –Size, balance and bound concepts
  - –Predict performance in terms of system weight, cost and technology applied
- Facilitates "Optimization, Allocation & Balancing" of System capabilities and performance such that:
  - –Combat/Force Effectiveness is Maximized
  - –System Performance is Maximized
  - –Cost, Weight and Operational Constraints are Satisfied
- Provides rapid means to conduct Tech/Risk/Cost (CAIV) assessments of technology, systems and sub-systems



"Automate" and capture the methodology and development knowledge base in a flexible, interactive tool

Causal Network Diagramming (CND)

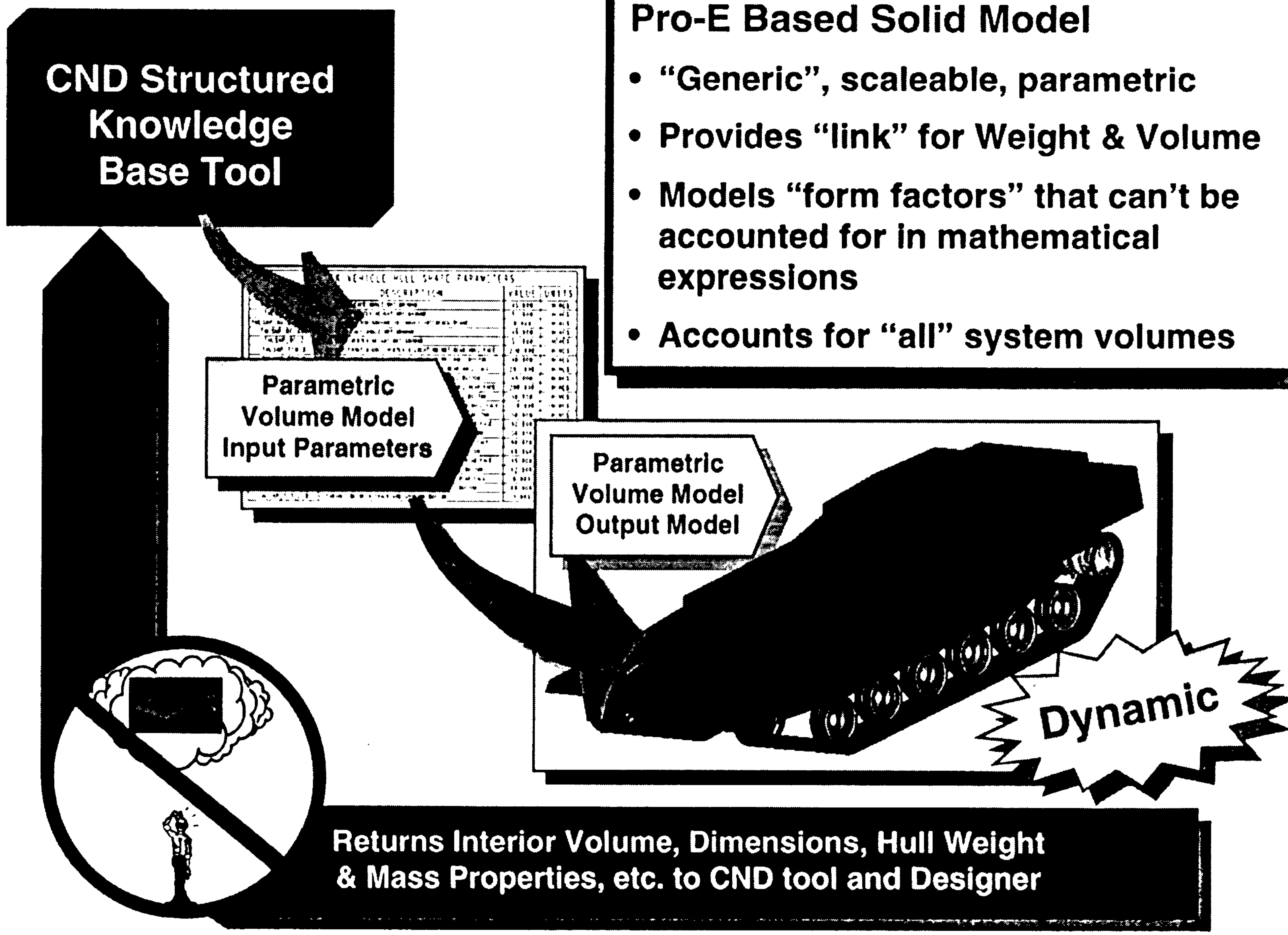


The CND provides a structured framework to capture the architectural, functional and technical knowledge base in way that can be used in an "automated" tool environment

dea001.ppt

Advanced Systems Development

Pro-E Parametric Volume Model Link



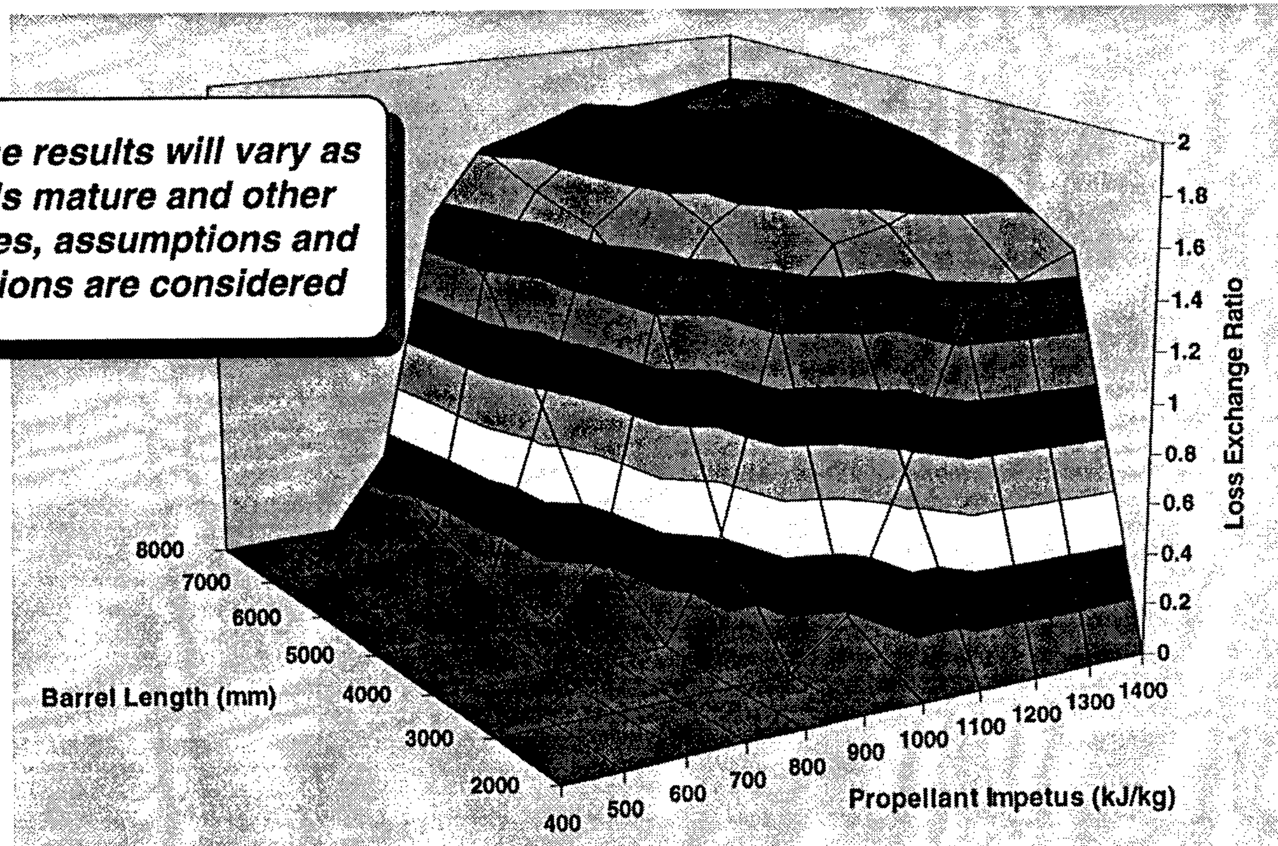
Pro-E Based Solid Model

- "Generic", scaleable, parametric
- Provides "link" for Weight & Volume
- Models "form factors" that can't be accounted for in mathematical expressions
- Accounts for "all" system volumes

Preliminary Results

- **Loss Exchange Ratio Example**

Note: These results will vary as the models mature and other technologies, assumptions and configurations are considered

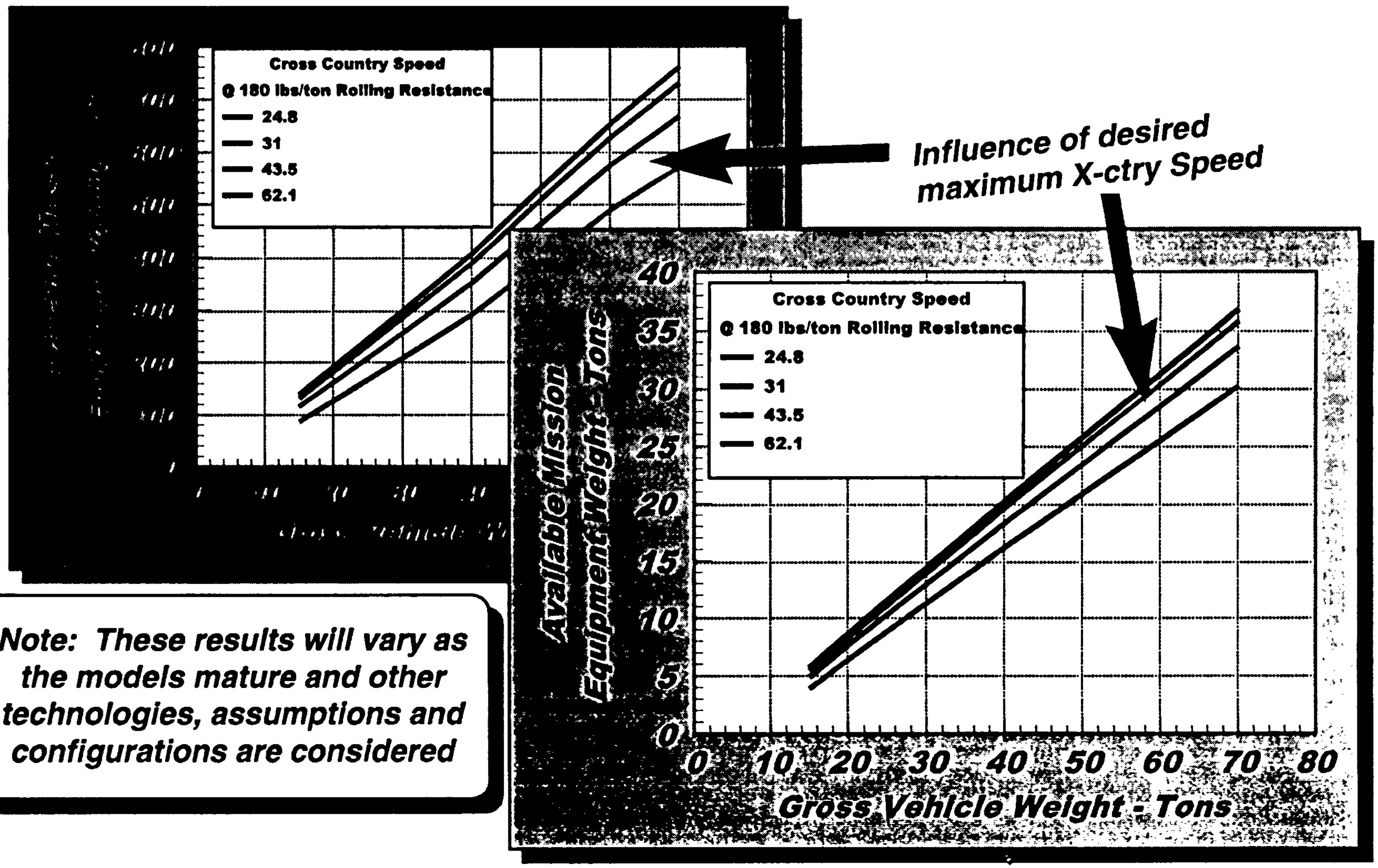


In addition to "automated" transfer of computed values within the tool, there are multiple output capabilities that can be tailored to specific needs of designer or evaluator in order to maximize the level of understanding

Preliminary Results - Cont'd

Available Mission Equipment Weight & Volume

. . . In Absolute Terms

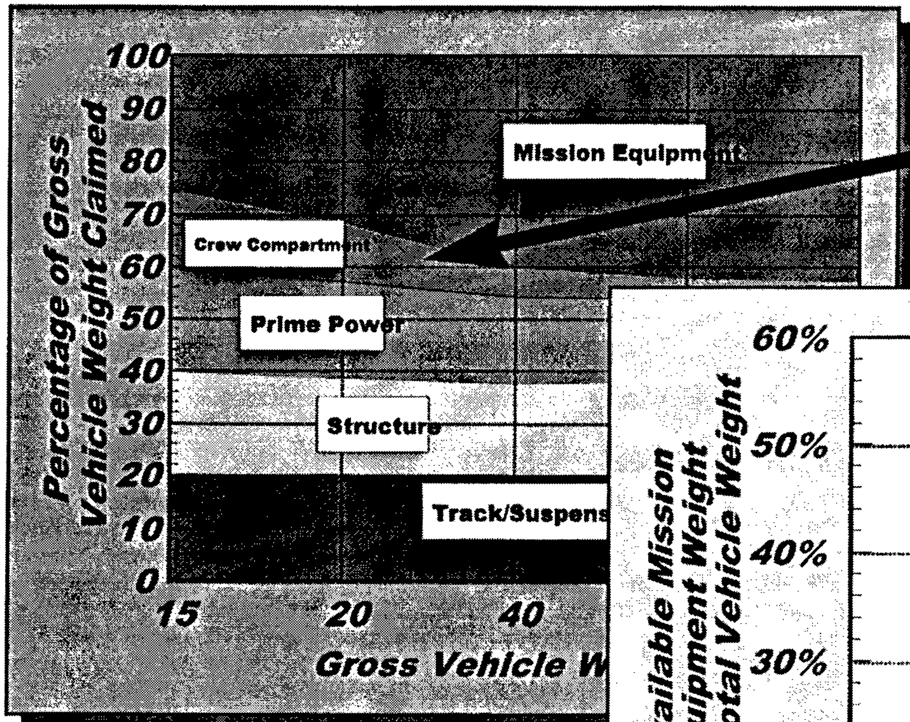


Note: These results will vary as the models mature and other technologies, assumptions and configurations are considered

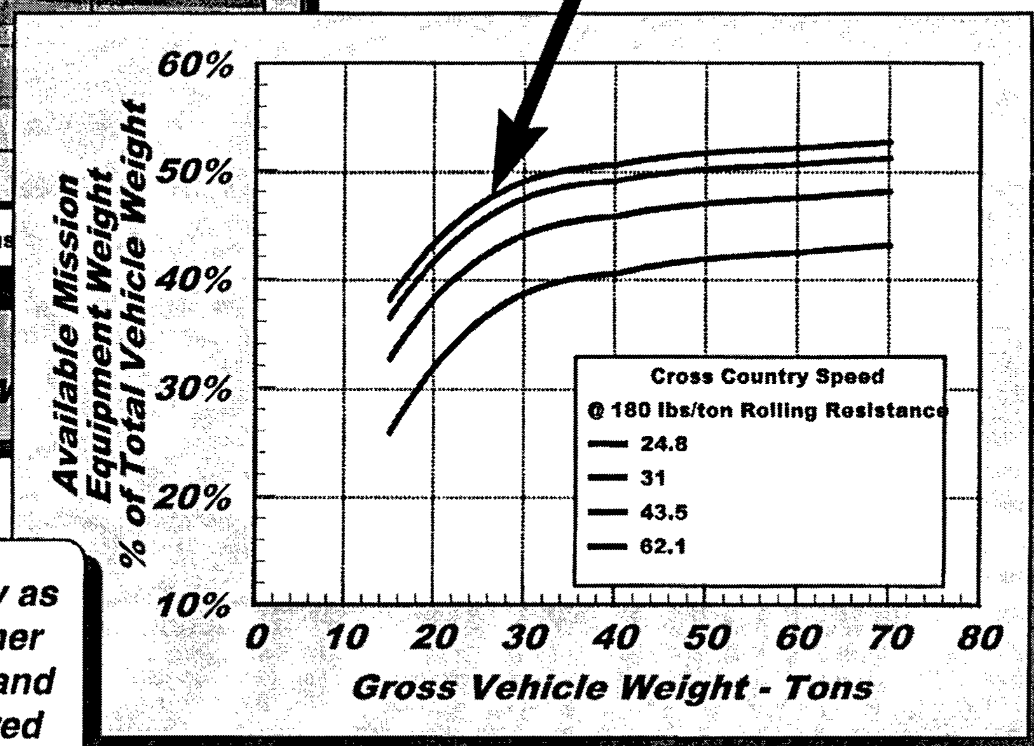
Preliminary Results - Cont'd

Available Mission Equipment Weight & Volume

. . . As a Percentage



Not everything, the crew for example, scales with GVW



Note: These results will vary as the models matures and other technologies, assumptions and configurations are considered

Advanced Systems Development

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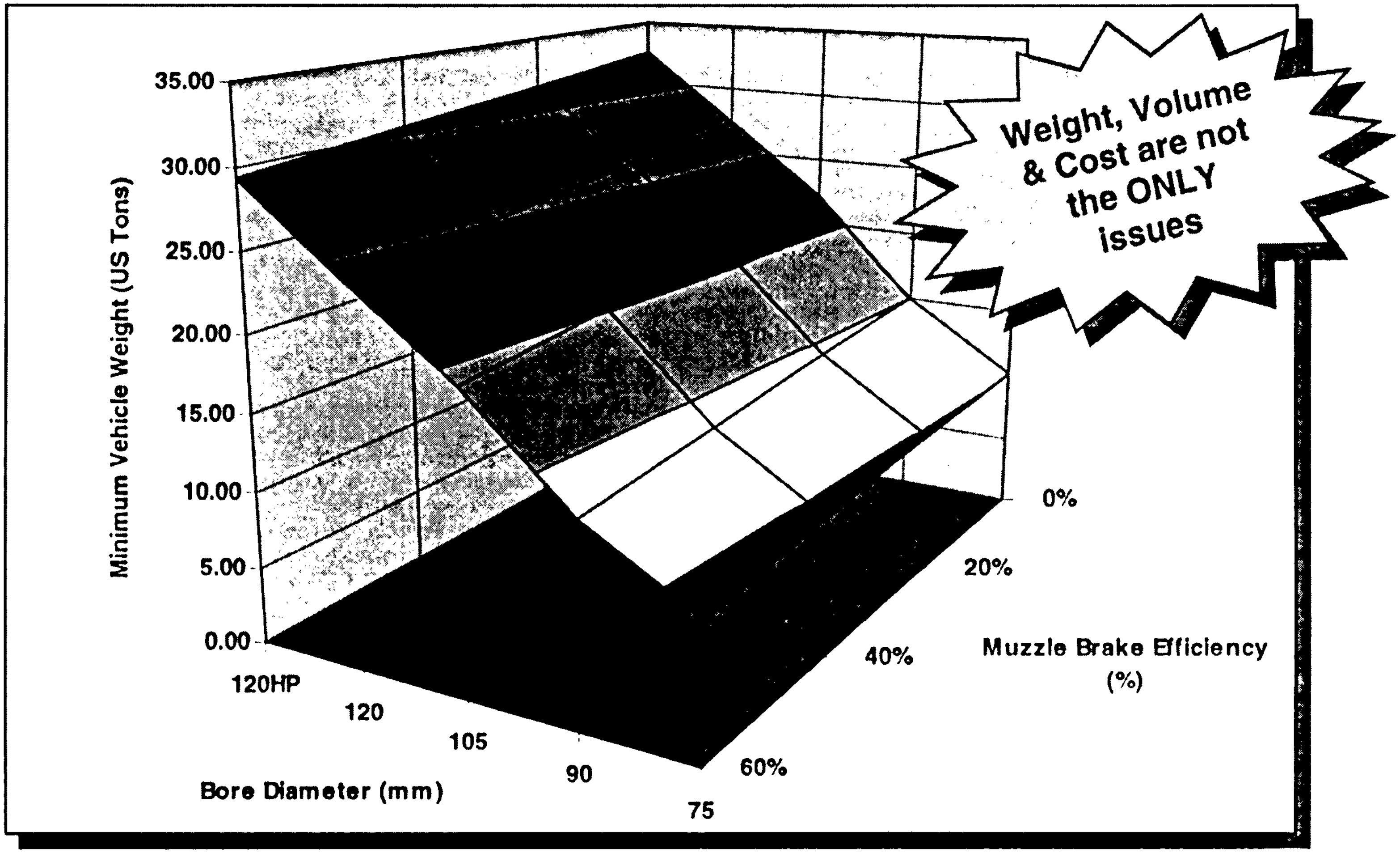
27-Jan-98, Page 15

Advanced Systems Development

Preliminary Results - Cont'd

Other Factors Need to be Considered:

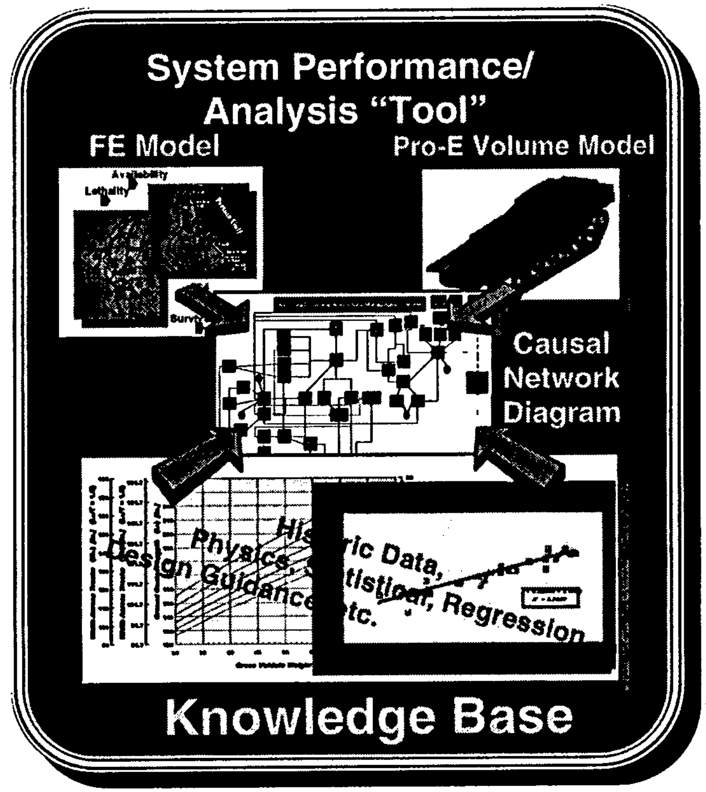
. . . Matching the Weapon Size to GVW Limits



Minimum Vehicle Weight vs Gun Impulse

What Does the CND Based Tool Bring to System Concept Development & Analysis?

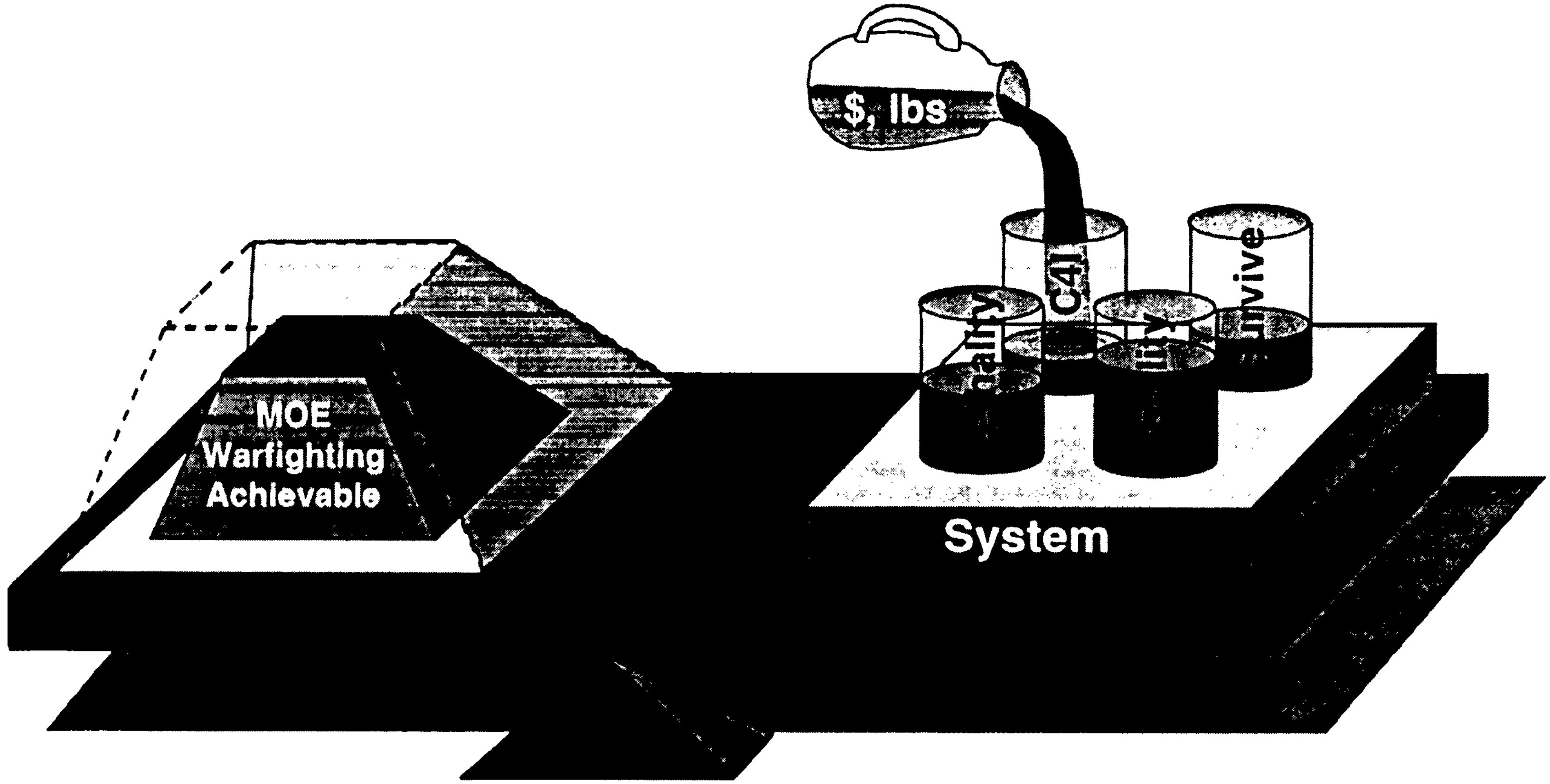
- Creates a "Dynamic" Network of System Performance, Cost, Weight, Volume, etc.
- Highlights Synergistic/ Conflicting Performance Requirements
- Identifies Areas Requiring Additional Analysis
- Provides Ability to Perform Quick Turnaround Tradeoff Analysis in the Context of the *System*



Identify "High Payoff" Performance Requirements
Identify "Heavy Hitters" in Cost/Weight
Identify What Capabilities are "Achievable"
Identify What the Technology "Needs to Achieve"

Advanced Systems Development

System Development Bottom Line



Constrained Resources (Cost, Volume & Weight) Need to be Allocated In a Way that Maximizes Warfighting Capability

DEFENSE SPECIAL WEAPONS AGENCY

Army/DSWA ETC Direct Fire Program

Plasma-Propellant Diagnostics Under the Army/DSWA ETC Program

Gary Phillips
C.C. Hsiao
Rex Richardson
Lindsey Thornhill

WORKSHOP ON ELECTROTHERMAL-CHEMICAL GUN PROPULSION TECHNOLOGY

Army Research Laboratory

January 27-28, 1998

Aberdeen Proving Ground, MD

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Overview

- Motivation for studying plasma-propellant interaction
- Description of the issues associated with understanding this interaction
- Our approach to addressing plasma-propellant interaction issues
  - Description of diagnostics and supporting analyses
- Initial characterization of igniter plasma optical properties
- Conclusions from initial optical measurements
- Description of efforts currently on-going or planned

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Need for Plasma-Propellant Interaction Study

- Propellant burn rate is temperature dependent
  - $JA2^{70F} = 0.90\ JA2^{120F}$ (closed bomb)
  - $TPEs^{70F} = 0.95 TPEs^{120F}$ (closed bomb)
- Modeling has demonstrated that performance sensitivity to BR increases as loading density increases

→ **Maintain desired performance level independent of ambient temperature**

- ARL EEF 120mm temperature compensation studies

→ **ETC 120 mm firings have demonstrated temperature compensation**

- ARL lead
- Direct Fire experiments & modeling provide support

→ **Plasma-Propellant Interaction Study**

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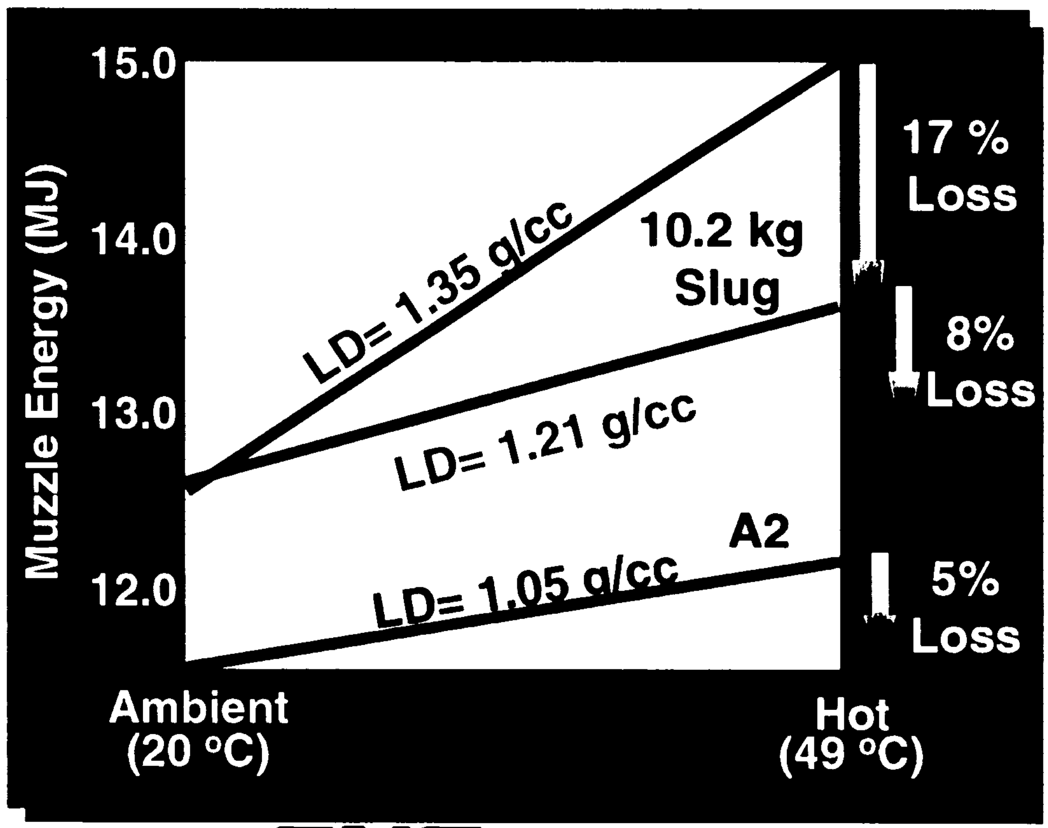
Increasing Loading Density

Higher charge mass results in higher performance fall-off with ambient temperature

- Thiokol 2nd Gen. formulations $(B_r)_{amb} = 0.96\ (B_r)_{hot}$
- Thiokol 1st Gen. formulations $(B_r)_{amb} = 0.96\ (B_r)_{hot}$
- JA2 $(B_r)_{amb} = 0.9\ (B_r)_{hot}$



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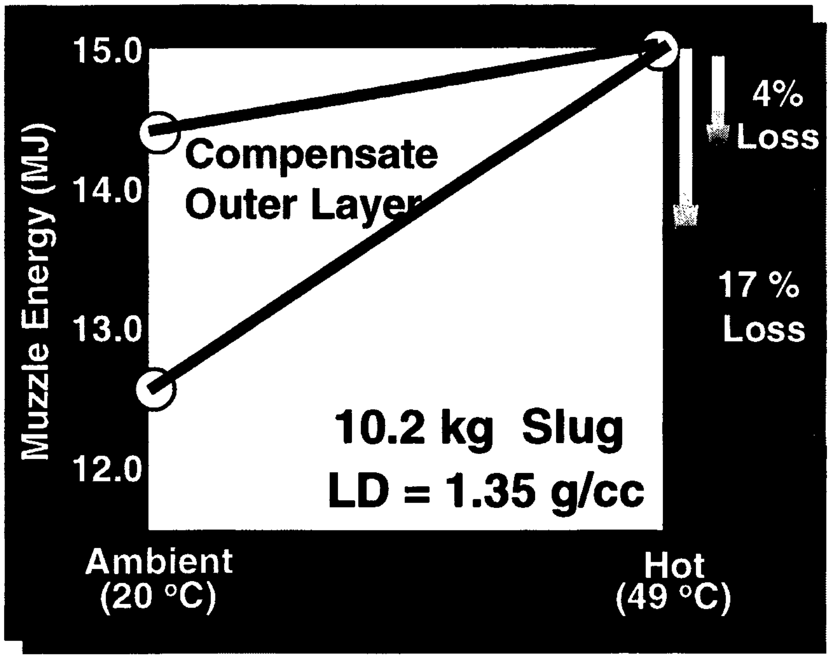
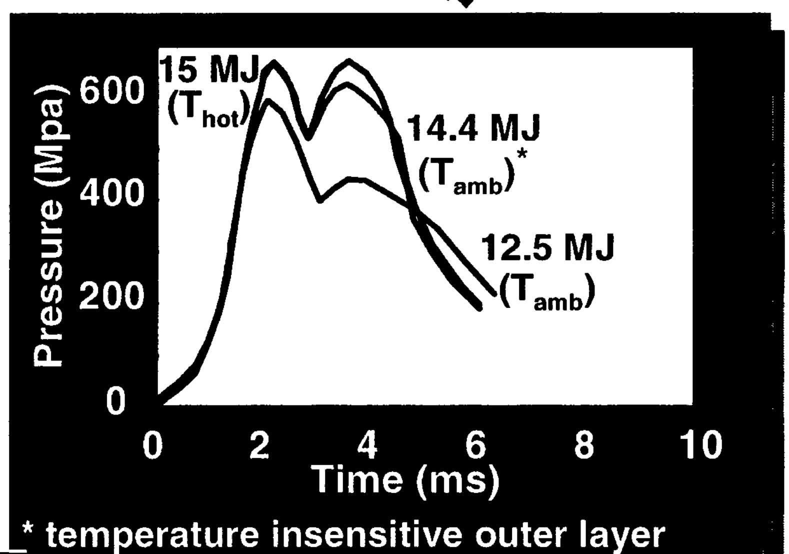
ETC Can Compensate for Performance Fall-Off with Temperature





- Thiokol 2nd Gen. formulations
  $(B_r)_{amb} = 0.96\ (B_r)_{hot}$
- Thiokol 2nd Gen. formulations
  $(B_r)_{amb} = (B_r)_{hot}$ (outer layer)
  $B_r)_{amb} = 0.96\ (B_r)_{hot}$ (inner layer)

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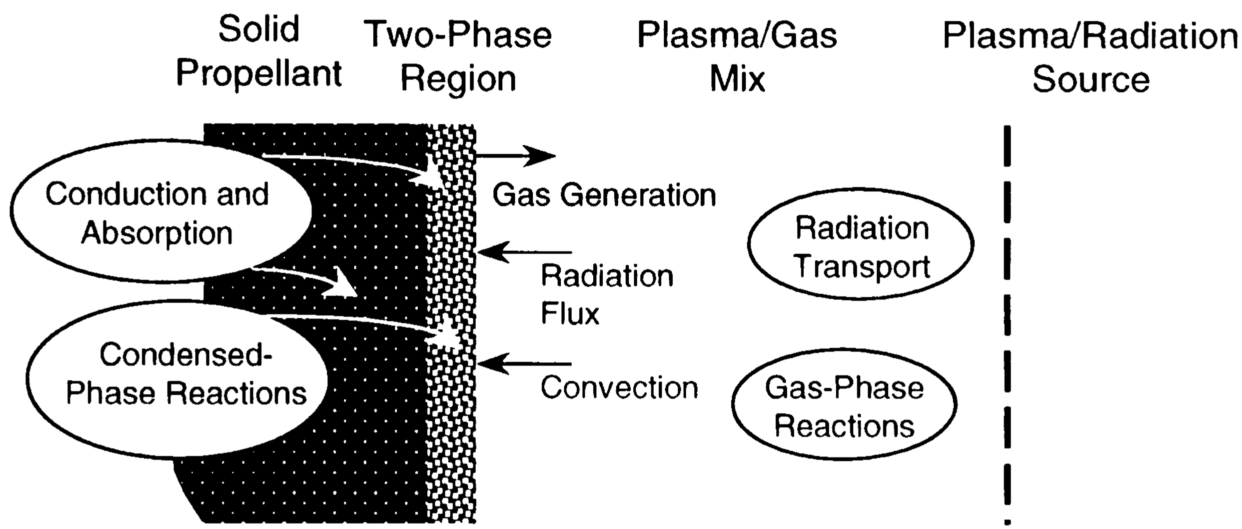
Propellant Environment is Very Complicated



- Initially, plasma (usually H, C, Cu, Al) evolves into the propellant chamber and begins to mix with the air in the ullage volume
- As propellant begins to vaporize, reaction products become part of the mixture
- Some propellant is directly exposed to the plasma source (i.e. line-of-sight) while other propellant is exposed only to the evolving plasma.

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Questions Needing Answers

- **How wide is the time window in which ignition and combustion can be influenced by the plasma igniter (i.e. do the evolving propellant/product gases effectively cut off this influence at some time)?**
- **What are the dominant modes of energy transport to the propellant?**
  - What are the relative contributions from convection and radiation?
  - What are the influences of p, T, composition and location in the charge?
  - Is energy deposited in gases or the solid propellant and what is the effect?
- **How does dominant transport mechanism scale with electrical power?**
- **How does transport vary among igniter concepts?**
- **How is electrical energy input related to plasma properties (temperature, species, density)?**
  - peak power
  - pulse width
  - total energy

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More Questions

- **What are the primary mechanisms responsible for BR augmentation?**
  - Are they primarily thermal?
    - Are reaction rates increased due to temperature-dependent kinetics?
    - Are gas generation rates increased due to radiant heating of propellant surfaces?
    - Is there an increase in the heat transfer coefficient?
  - Are they primarily chemical?
    - Do plasma species alter/improve reaction pathways (e.g. electron kinetics, ion kinetics, presence of highly-reactive radicals)?
    - Does resonant absorption alter/improve reaction pathways (i.e. photochemistry)?
- **Is there significant in-depth heating of the propellant due to absorption?**
- **What are the optimal propellant/plasma properties to either promote or deter this heating?**
- **What are the parameters controlling interaction?**
  - What are the propellant/burn products optical properties?
  - What are the conduction/convection time scales?
  - What is the plasma distribution?

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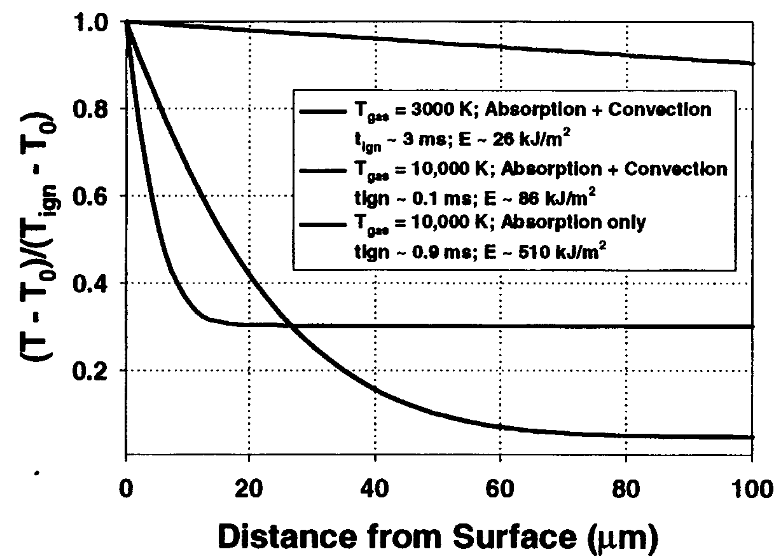
Potential In-Depth Temperature Profiles at Ignition

- These profiles are based on a simple 1D model of propellant heating
- Each profile corresponds to a snap shot at the moment the propellant surface reaches an ignition temperature



Significant in-depth heating of propellant is possible if a sufficient fraction of the ignition energy is coupled to the propellant by radiation transport - depends on the intensity and spectral character of the radiation, the absorption properties of the propellant and the time of exposure

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Optimizing EE for Temperature Compensation

- Experiments
  - Time-integrated spectra (some concepts)
  - Time-dependent spectra for each igniter concept
  - Heat flux (convecitve, radiative)
- Modeling
  - BISON chamber environment predictions
  - Igniter properties predictions for each concept

- Experiments
  - Solid phase extinction coeff for inventory propellants
  - Solid phase extinction coeff for advanced propellants
  - Plasma-adv propellant interaction exps (ARL open air)

- Experiments
  - ETC closed bomb testing
  - 60 mm temp. sensitivity studies (hardware & propellant)
  - 120 mm temp. sensitivity & compensation (EEF, DF)
- Modeling
  - 1D time-dependent detailed chemistry model to study ignition & burn rate sensitivity as a funct. of spatial variations in external energy deposition (FORTEL)
  - 1D time-dependent engineering, single step plasma/propellant interaction model
    - compare with detailed FORTEL model
    - validate against data
  - EEF data analyses
    - ARL
    - Direct Fire

Plasma Characterization

+

Propellant Characterization

=

Understanding Interaction

Designs that optimize use of ETC

■ On-going ■ TBD

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Optical Radiation Characterization

- Five subscale tests were dedicated to initial measurements of igniter discharge optical radiation properties.
- The results are being used in refining plasma/propellant interaction models.
- A silicon photodiode was used to obtain the emission waveform and infer total radiated power (TRP).
- An Ocean Optics 2000 fiber optic spectrometer was used to obtain a time integrated spectrum in the 200-1000 nm range. The system was calibrated from 350-1000 nm using a fiber optic coupled QTH lamp (3200 K).

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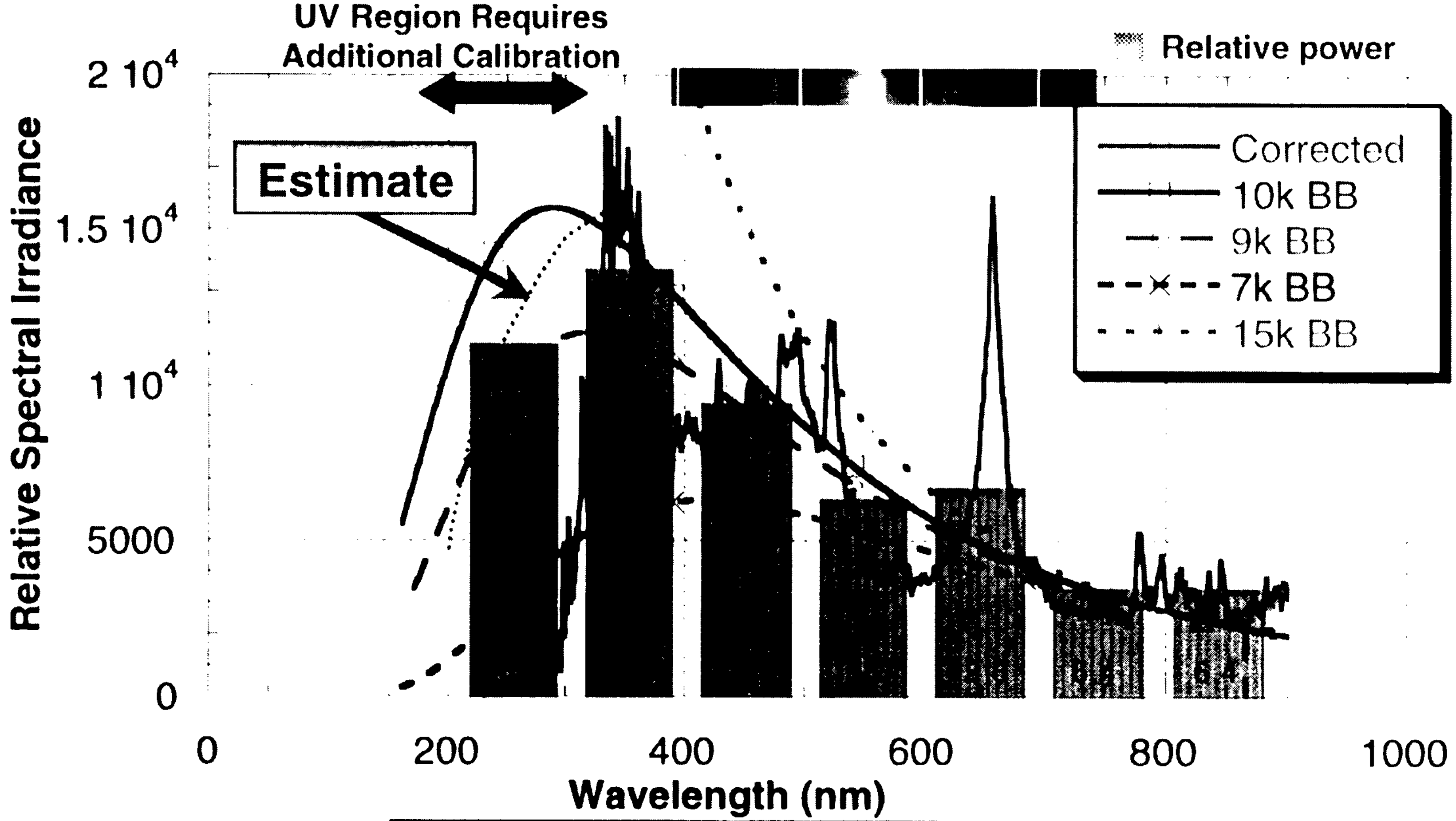
Spectrum at Propellant Surface



63% of Radiative Power @ $\lambda < 500$ nm

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Summary of Igniter Optical Data

- Time integrated spectral measurements:
  - The igniter discharge has a spectrum typical of high pressure arc plasmas (pressure broadened lines and bands on a gray body continuum).
  - The spectrum is very repeatable for the conditions tested
- Total radiated power measurements:
  - Calibrated and spectrally corrected Si photodiode data show a peak TRP, for subscale igniter configuration, to be about 50% of peak electrical input.
  - The signals are highly repeatable.
- The initial assumption of high radiation output is confirmed.
- These results are being implemented in plasma/propellant interaction models.

Efforts Currently Planned or Underway

- SAIC staff plan to further characterize plasma sources currently being considered with spectroscopy and calorimeter measurements
- ARL staff plan to determine absorption coefficients for the Indian Head, Thiokol and Aerojet propellants of interest using a UV-rich source
- ARL staff plan to conduct open-air pyrolysis tests with outer-layer propellant materials characterizing the heat flux to the propellant and the propellant response - these tests will include an assessment of temperature sensitivity
- FORTEL staff are completing a parametric study of the influence of varying spatial distributions of energy deposition on propellant burn rate
- SAIC staff are using BISON and IBHVG2 to analyze EEF temperature-compensation data to determine the role of thermal mechanisms in explaining the test data
- SAIC staff are continuing refinement of engineering PPI model
  - Implementing a multi-band absorption model
  - Extending model through ignition to steady-state burning
  - Model will be validated against test data and FORTEL calculations

WEAPONS & MATERIALS RESEARCH DIRECTORATE
ABERDEEN PROVING GROUND

Basic Research on the Chemistry of Plasma/Propellant Interactions

Rose Pesce-Rodriguez

Pam Kaste

Workshop on Electrothermal-Chemical Gun Propulsion
Under the Auspices of the German-US DEA-G-1060
January 28, 1998

Outline

- Presentation of results from several "informal" examinations of plasma-exposed gun propellants
- Discussion of proposed basic research work-unit on plasma/propellant interactions.

Plasma* Exposure Experiments

- JA2 Sheet (Mar 95)
  - 60 MW power
  - exposed through polyethylene tube (radiation effects dominate)
- JA2 grains (Jul 97)
  - 60 MW power
  - exposed directly to plasma
  - shielded by aluminum foil (conductive effect only)
  - shielded by mylar (radiative effect only)
- Propellant array (Aug 97)
  - 125 MW power
    - plasma distribution *not* uniform over sample array
  - exposed and mylar-shielded
    - JA2. M9, XM39-like propellant (all grains)

* in all cases, plasmas not characterized

Plasma-Propellant Interaction Set-up

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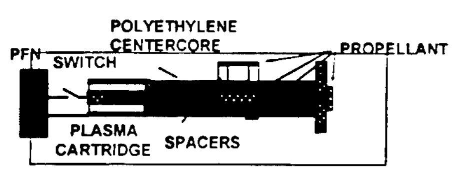
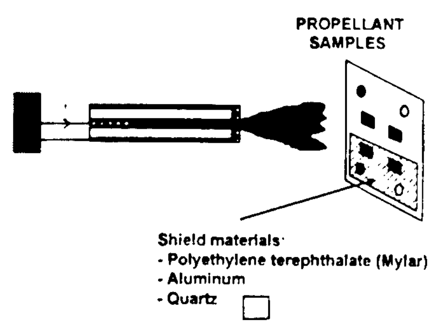


Plasma exposure through polyethylene tube

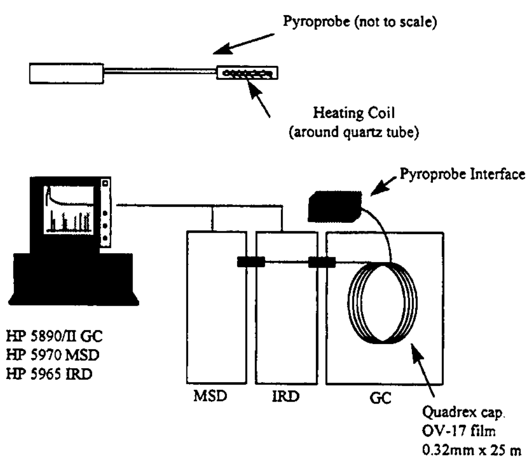


"Open air" exposure to plasma

JA2 Sheet, Through PE Tube

(Mar 95 Sample)

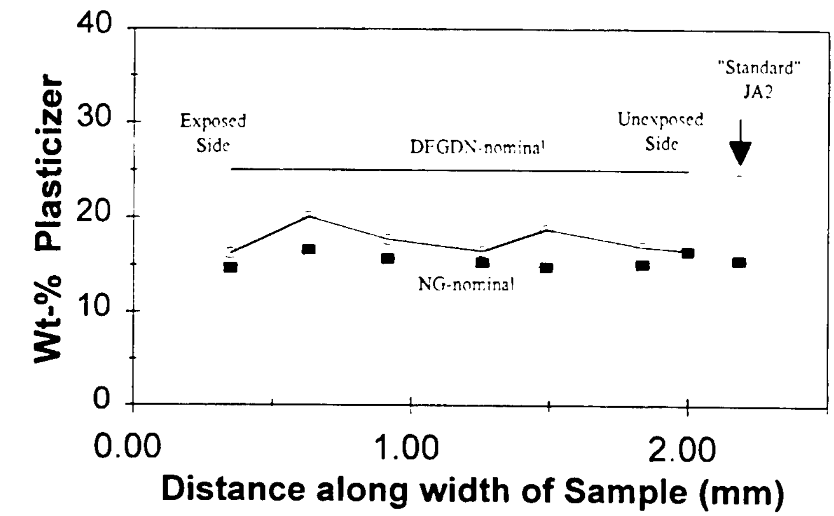
- 60 MW power (plasma)
- SEM examination (Rob Lieb, ARL)
  - Evidence of subsurface reaction
    - melting and possible chemical reaction
    - reaction to depth of approximately 1 mm
    - voids larger as one proceeds deeper into sample
    - surface appears to be "peeled up" (from escaping gases?)
- Chemical analysis
  - IR: not performed
  - Desorption-GC-MS:
    - Preferential depletion of DEGDN plasticizer



Experimental Apparatus for D-GC-MS Experiments

Plasticizer Profile by GC-MS

Plasma-treated JA2. Mar 95 Sample)



Conclusion Based on "Through-the-Tube" Experiment?

- Radiation alone *appears* to be sufficient to initiate physical and chemical changes in JA2 propellant.

  but...

- Experiment has not been reproduced.

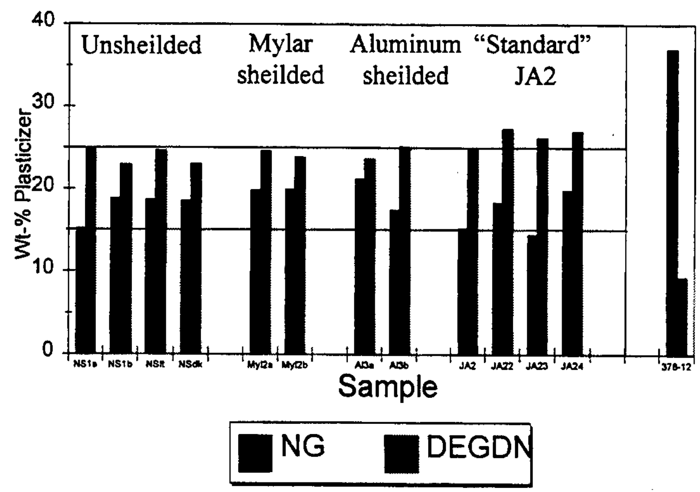
JA2 Grain; Un/Shielded

(Jul 97 Sample)

- 60 MW power
- Chemical characterization
  - SEM: not performed
  - D-GC-MS:
    - No notable difference in level of either plasticizer after treatment of any of the samples
  - IR:
    - Suggests that convective effects dominate.

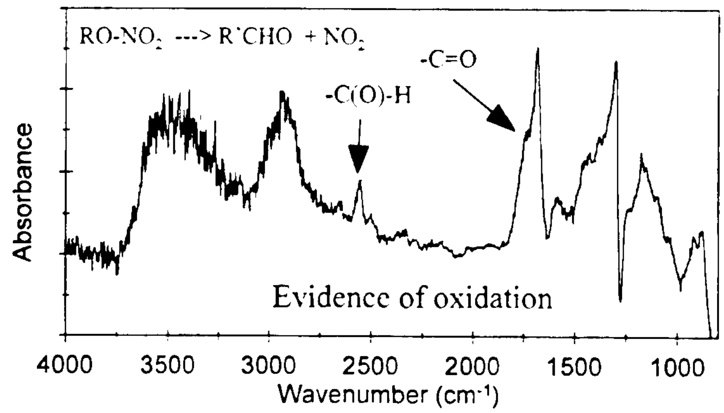
Plasticizer Level by D-GC-MS

(Plasma-Treated JA2; Jul 97 Samples)



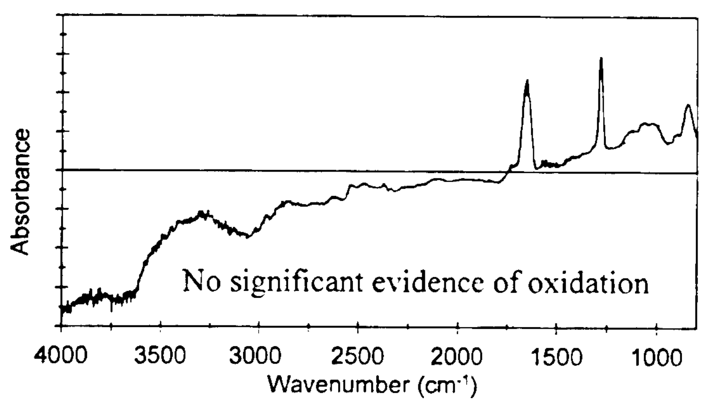
JA2; Unsheilded

(full plasma effect)



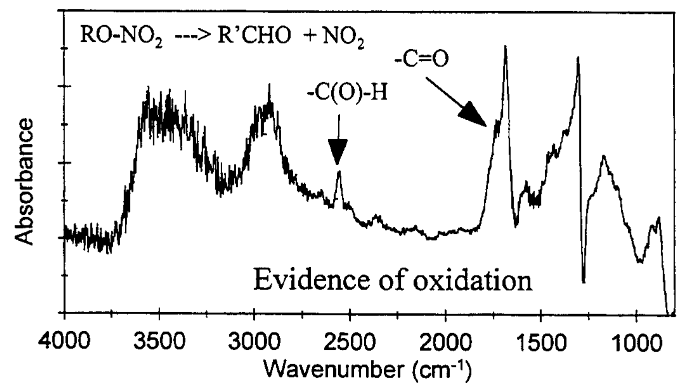
JA2; Mylar Shield

(radiative effect)



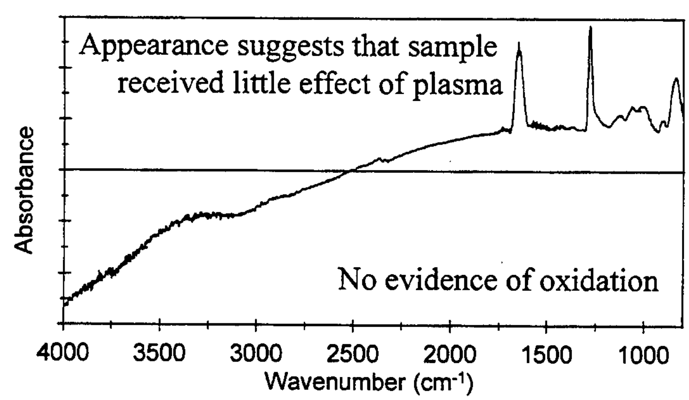
JA2; Aluminum Foil Shield-A

(convective effect)



JA2; Aluminum Foil Shield-B

(convective effect)



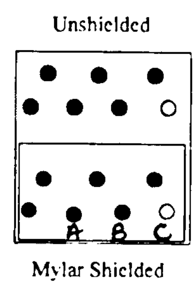
Conclusion Based on this "Open air" Experiment?

- Although the same power was used in both the "through-the-tube" and the "open air" experiments, results are quite different.
  - No obvious loss of plasticizer.
  - Radiation dominant for "t-t-t"; convective dominant for "open air".
- Additional experiments of both type are necessary before real conclusions can be drawn.

Propellant Array; Un/Shielded

Microreflectance -FTIR Analysis

(Aug 97 Sample)



- 125 MW power (plasma)
- A ● M9
  - Unshielded: appearance of carbonyl absorbance
  - Mylar shielded: no notable change
- B ● JA2
  - Unshielded: burned, no residue remained
  - Mylar shielded: no notable changes
- C ○ XM39-like propellant
  - Unshielded: no notable change
  - Mylar shielded: decreases carbonyl absorbance
    - possibly due to loss of acetyl and butyryl groups

Conclusion Based on this "Open air" Array Experiment?

- Assuming uniform exposure (valid?):
  - At high power, direct exposure to plasma will ignite JA2, but not M9 and XM39-like propellant.
  - Radiation effects alone are sufficient to induce chemical changes in XM39-like propellant, but not in JA2 and M9.
    - (For JA2) Inconsistent with "through-the-tube" experiment, but consistent with "open air" experiment.
- More experiments are necessary.

Conclusions for Experimental Work

- Examples of the type of experiments that can be done were shown.
- Experiments have not been reproduced.
- Results appear to be inconsistent, but perhaps we should not expect the same result from experiments performed under different experimental conditions.
  - What can we learn from the differences?

Proposed FY99 Work Unit on PPI

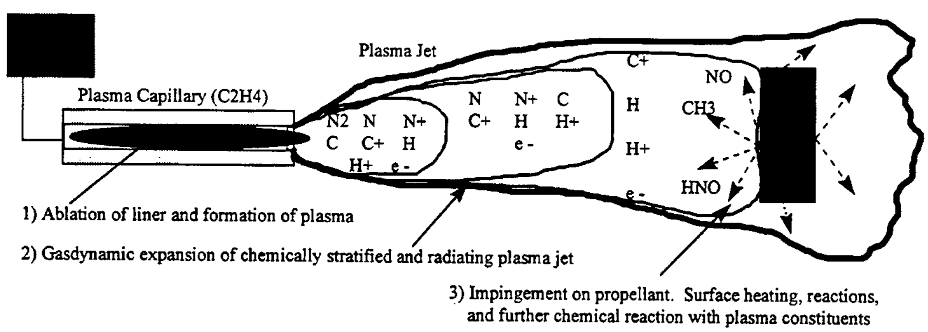
(Approval uncertain.)

- Objective
  - Identification of design rules for advanced propellant formulation based on optimized plasma/propellant coupling.
- Payoff
  - Exploitation of benefits of plasma-based ignition
    - short, reproducible ignition delay
    - temperature insensitivity
  - Improved gun performance

FY99 Deliverables

- PPI model based on:
  - Constitutive model of plasma
  - CFD simulation of simplified plasma jet impingement on a solid surface
  - Chemical reactions between plasma components and propellants
- Determination of effects of radiative, convective, and chemical components of plasmas on mechanical properties and chemical decomposition processes
  - Based on characterization of propellants (with varying formulations) from "interrupted burn" experiments

Modeling Plasma-Propellant Interaction



<u>OVERALL MODEL REQUIRES INTERACTION OF SUBMODELS:</u>

1) Model the formation of the plasma constituents, spectral properties, radiation and energy content, temperature, density, velocity, pressure, etc. (M. McQuaid).
2) Model the formation of the plasma jet outside the capillary, including gasdynamic expansion, turbulence, chemical stratificaton, reaction, & radiation effects (M. Nusca).
3) Model the chemical kinetics for interaction of the plasma constituents with propellant slab, including subsequent gaseous reactions in the plasma (W. Anderson).

(Nusca, 1/98)

Chemical and mechanical properties characterization will take place independently of modeling effort...

...but, for the interpretation of experimental results, will rely on most of the same information needed for model.

(Beck-Tan, Kaste, Lieb, Pesce-Rodriguez, Schroeder)

Approach:

- **Examine a series of propellants with different formulations (e.g. single base, double base, triple base, ETPE, LOVA).**
  - Ignition by plasma-based and conventional igniters
  - "Shielded" samples (Mylar, aluminum foil)
- **Characterize chemical and physical changes induced by igniter.**
- **Determine effects of radiative, convective, and chemical components of plasmas.**
- **Correlate response to igniters with formulation (ingredients, functional groups, etc).**
  - Deduce design rules from observed correlations.

Related Support:

- The Army Research Office has been briefed on our current and future activities and is very supportive. They have pledged to help out in any way possible (workshop of experts may be held).
- ARL will exploit expertise in academia and industry as appropriate.
  - Penn State hosted on 3 Dec 97 and 16 Dec 97
  - Expert on ion chemistry to lecture at ARL in early March 98
- JANNAF Workshop on PPI scheduled for May 97 (ARL will host).
- "DRI" (an internal ARL funding source) proposal to investigate chemistry and temperature at surface of plasma-ignited propellant (real time) funded.

Proposed Applied Research Program

- Approval uncertain.
- Proposed activities:
  - Investigation of surface integrity
    - Based on imaging of grains immediately after extinguishment (via blow-out disk)
  - Comparision of relative merits of igniters based on organic and non-organic materials

Overall Conclusion

We have big plans for some exciting research…

…and expect to have much more information to share at the next DEA meeting!

ETC Closed Chamber Experiments

Miguel Del Güercio

Weapons & Materials Research Directorate
Army Research Laboratory,
Aberdeen Proving Ground, MD

DEA-G-1060
German/US Workshop on
Electrothermal-Chemical Gun Propulsion
27-28 January 1998, Aberdeen Proving Ground

PROPOSED QUESTIONS

DEA 1060, 27-28 January 1998

1. What kind of theoretical considerations concerning the plasma/propellant interaction have been performed?

2. Do you have appropriate modeling tools to calculate ETC effects in comparison to conventional ignition and how do they work (detailed energy release in space and time or simply lumped parameters, energy added globally as heat)?

3. Are radiation effects taken into account in these models?

4. Do you have measured time and wavelength resolved spectra of the plasma and/or burning propellant?

5. What type of experimental setup has been considered to be promising in studying the ETC effect?

6. Which closed vessel experiments have been performed in the last five years to examine the interaction between plasma and burning propellant?
   - types of closed vessel arrangements
   - pressure range of experiments
   - loading density and type(s) of propellant
   - results of different setups (load configurations) and possible explanation of behavior

7. Which type(s) of power supply has been used? single pulse, sequential triggering

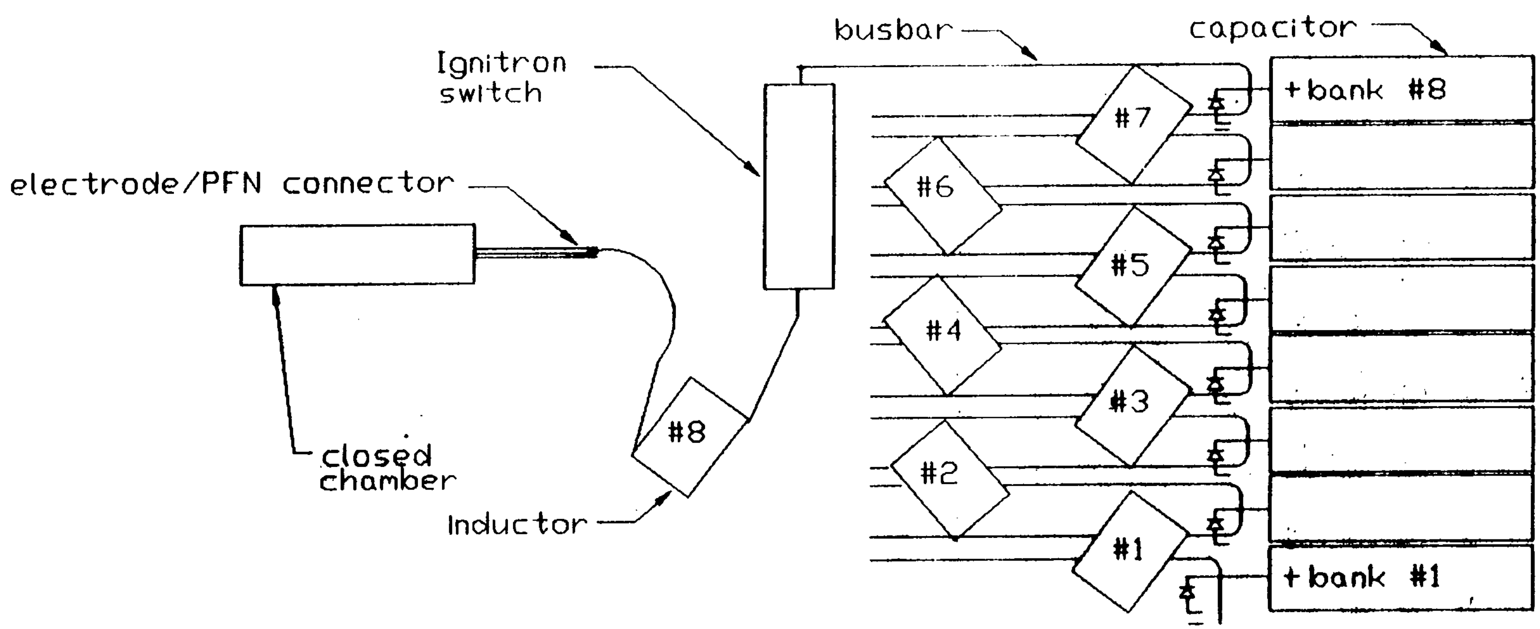
8. Which type of energy converter has been used (e.g. piccolo-type, multi-electrode)

9. Which type of firing experiments have been performed during the last five years?
   - powder charge arrangements and type of energy release
   - caliber, barrel length, chamber volume
   - results, especially muzzle velocity and ballistic efficiency

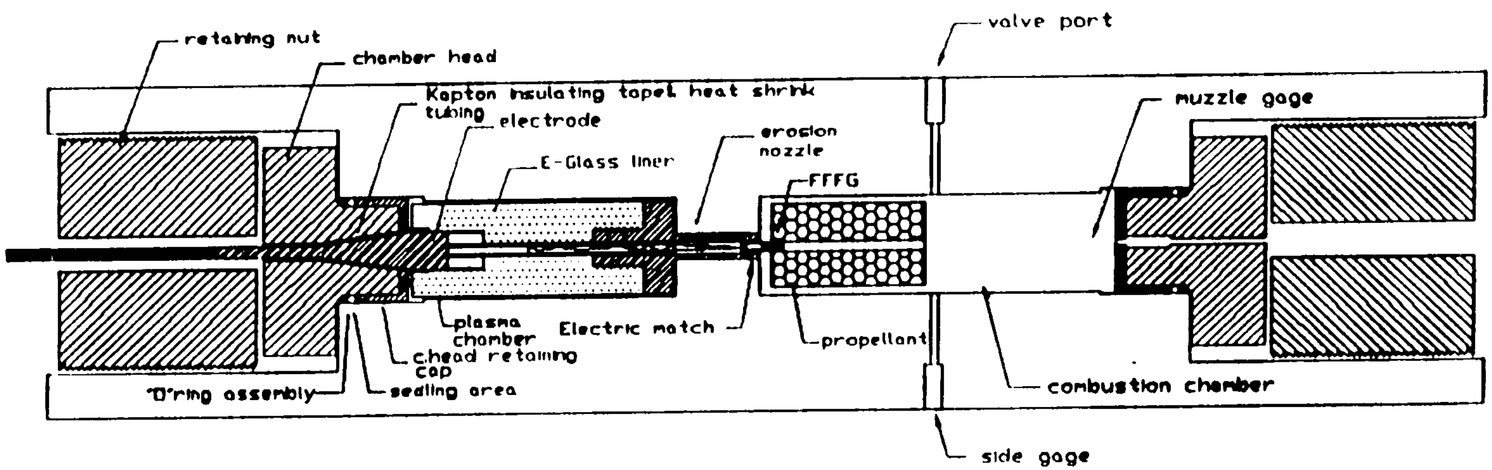
OUTLINE

- Hardware
- JA2 Firings
  - Variable Pulse Width
  - Temperature Sensivity
  - Plasma Delay
- Capillary Optimization
- Propellant Study
- Future Work

PFN SCHEMATIC



CONVENTIONAL CHAMBER SET UP



120cc combustion chamber
9cc plasma capillary cavity

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ETC CHAMBER SET UP

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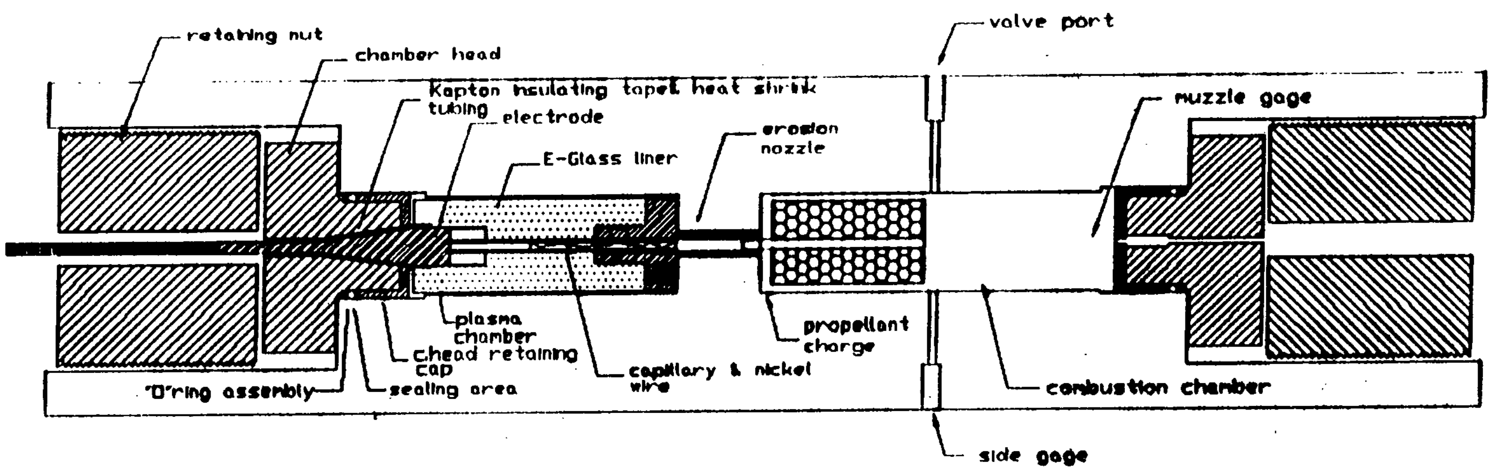

120cc combustion chamber
9cc plasma capillary cavity

PLASMA DELAY CHAMBER SET UP

ABERDEEN PROVING GROUND

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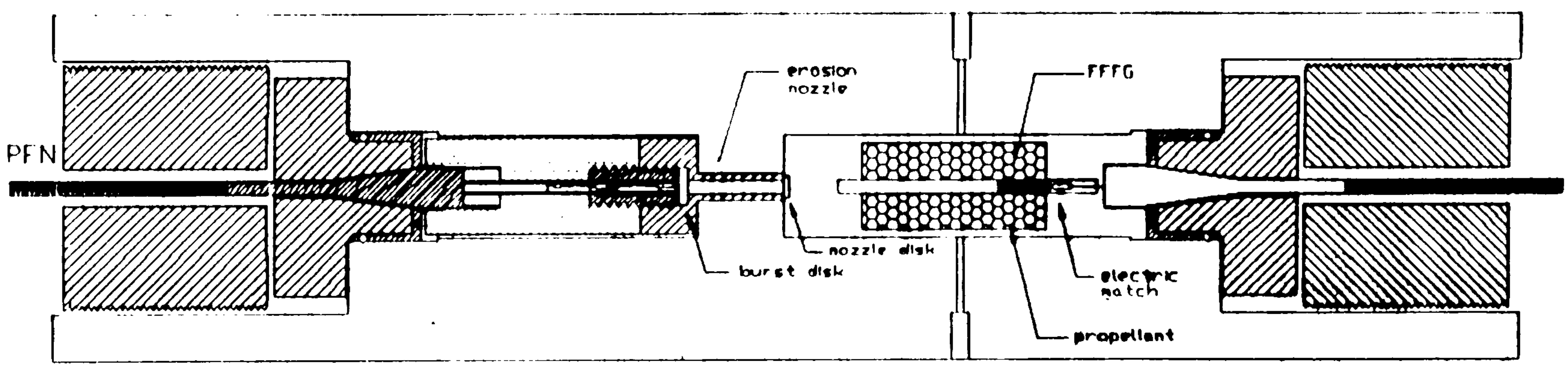


120cc combustion chamber
9cc plasma capillary cavity

JA2 ETC FIRINGS

SHOT ID	JA2 DISKS (g/cc)	PFN BANKS VOLTAGE (kV)	PFN PULSE WIDTH (ms)	PRESSURE MAX (MPa)	E.ENERGY DENSITY (kJ/g)
12103S2	0.21	—	—	294	—
03154S2	0.21	3	1.2	318	0.6
03184S2	0.27	3	1.2	417	0.46
04084S1	0.22	5	1.2	322	1.27
04194S1	0.21	5	1.2	320	0.8
08314S1	0.18	5	2.4	237	2.41
09164S1	0.18	5	2.4	238	2.62

JA2 TEMPERATURE SENSITIVITY FIRINGS

ABERDEEN PROVING GROUND

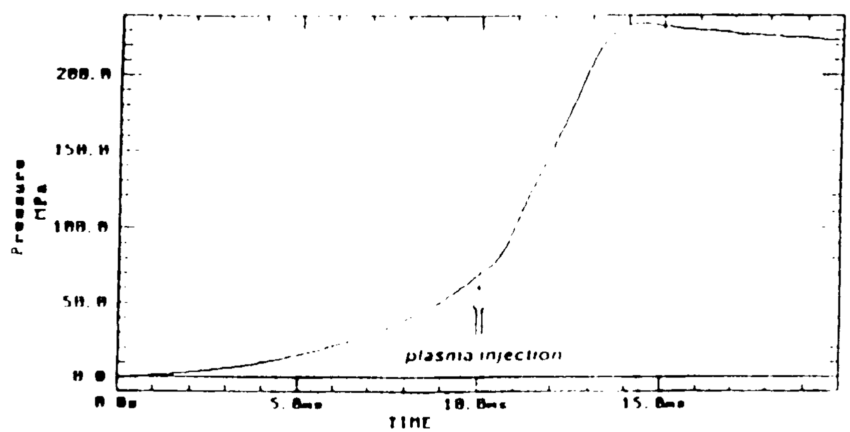
WEAPONS & MATERIALS RESEARCH DIRECTORATE

SHOT ID	T C^0	JA2 7PERF (g/cc)	PFN BANKS VOLTAGE (kV)	PFN PULSE WIDTH (ms)	PRESSURE MAX (MPa)	E.ENERGY DENSITY (kJ/g)
04255S7	21.1	0.23	—	—	248	—
04265S8	-31.7	0.22	—	—	232	—
04275S9	48.9	0.22	—	—	240	—
04115S1	21.1	0.21	4	1.2	276	0.78
04115S2	21.1	0.22	4	1.2	260	0.78
04125S3	48.9	0.22	4	1.2	270	0.82
04175S4	48.9	0.22	4	1.2	258	0.78
04205S5	-31.7	0.22	4	1.2	203	0.89
04205S6	-31.7	0.22	4	1.2	251	0.86

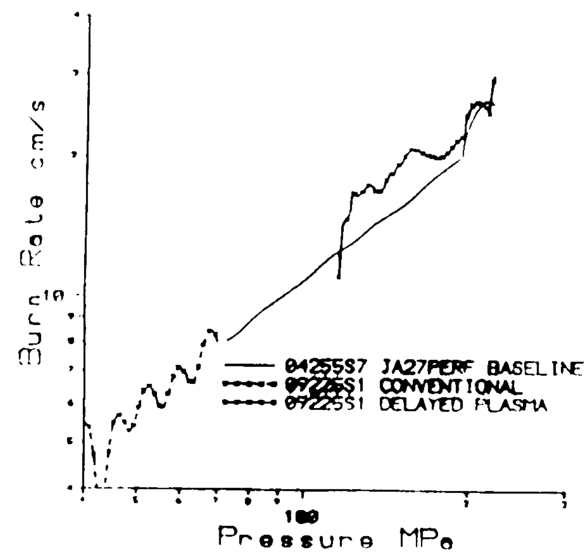
JA2 7PERF PLASMA DELAY FIRINGS

SHOT ID	JA2 7 PERF (g/cc)	PLASMA DELAY (ms)	PFN BANKS VOLTAGE (kV)	PFN PULSE WIDTH (ms)	PRESSURE MAX (MPa)	E.ENERGY DENSITY (kJ/g)
04255S7	0.21	—	—	—	266	—
09225S1	0.20	10	5	1.2	236	1.1
10025S1	0.21	10	5	1.2	255	0.96
10035S1	0.21	10	6.5	1.2	261	1.38
10055S1	0.21	2	3	1.2	251	0.37
10065S1	0.21	10	3	1.2	250	0.37

JA27PERF PLASMA DELAY FIRINGS



PRESSURE vs. TIME



BURN RATE vs. PRESSURE

M5 CAPILLARY OPTIMIZATION

ABERDEEN PROVING GROUND

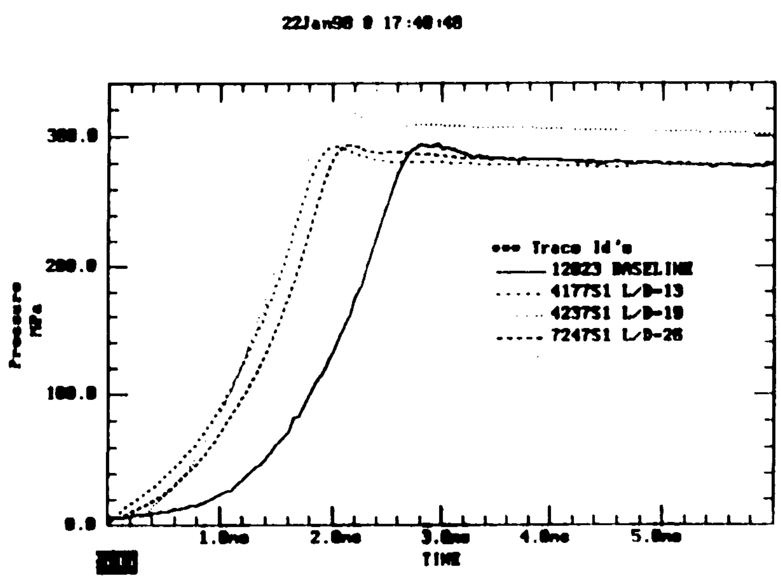
WEAPONS & MATERIALS RESEARCH DIRECTORATE

SHOT ID	M5 SINGLE PERF (g)	PLASMA CAPILLARY L/D	PFN BANKS VOLTAGE (kV)	PFN PULSE WIDTH (ms)	PRESSURE MAX (MPa)	E.ENERGY (kJ)
03127S1	—	26	4	1.2	123	25.7
03197S1	—	19	4	1.2	117.5	27.2
03267S1	—	13	4	1.2	100	27.5
12023	29.15	13	4	—	292	—
04177S1	29.0	13	4	1.2	292	24.3
04237S1	29.0	19	4	1.2	323	28.7
07247S1	29.0	26	4	1.2	293	25.0

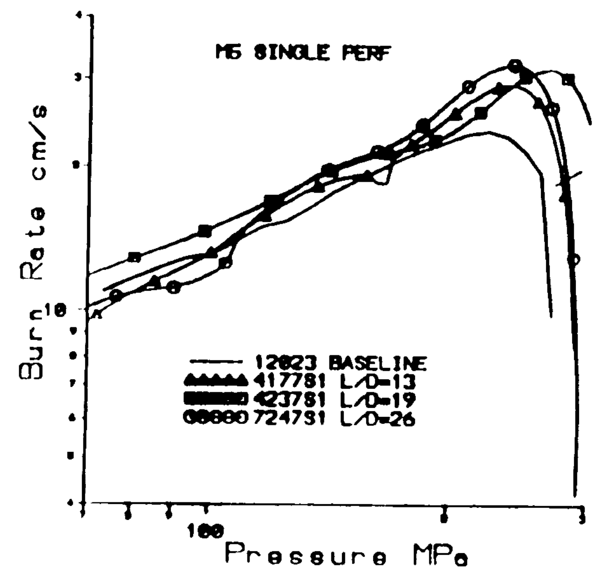
CAPILLARY OPTIMIZATION

ABERDEEN PROVING GROUND

WEAPONS & MATERIALS RESEARCH DIRECTORATE



M5 PRESSURE vs. TIME



M5 BURN RATE vs. PRESSURE

EXPERIMENTAL SET UP

- ***Closed chamber set up***
- ***Propellant selection***
- ***Firing Parameters:***
  - ***Plasma capillary of L/D=26 ratio***
  - ***Electrical Energy loading density of 0.8 kJ/g***
  - ***Same propellant loading configuration for conventional (base-line) and ETC firings***

OBJECTIVES

- *To determine the effect on burn-rate of ETC Closed Chamber plasma injection with the new capillary (L/D=26), for different classes of solid propellants (single, double, triple base and nitramine)*

PROPELLANT SELECTION

- Geometry for all propellants selected : 7-perf/cylindrical
- Propellant grain size: 1.5 cm length, .75 cm diameter
- Loading density was increased from .2 g/cc to .25 g/cc , to minimize heat loss

  Samples selected:
  - M10/Single Base: NC at 98%
  - JA2/Double Base: NC at 60%
  - NG at 16%
  - M30/Triple Base: NQ at 47%
  - NC at 28%
  - NG at 22.5%
  - XM39/Nitramine: RDX at 76%

    ATC at 7.6%

BASELINE FIRINGS

BASELINE SHOT ID	PROPELLANT TYPE	LOADING DENSITY (g/cc)	PRESSURE MAX (MPa)
9237S1	M10/SINGLE BASE	0.25	269
9247S1	M10/SINGLE BASE	0.25	276
4255S7	JA2/DOUBLE BASE	0.21	248
1077S1	JA2/DOUBLE BASE	0.25	291
10167S3	M30/TRIPLE BASE	0.25	298
10177S1	XM39/NITRAMINE	0.25	280

ETC FIRINGS

ETC SHOT ID	PROPELLANT TYPE	LOADING DENSITY (g/cc)	ELECTRICAL ENERGY DENSITY (kJ/g)	PRESSURE MAX (MPa)
1027S1	M10/SINGLE BASE	0.25	0.74	300
1037S1	M10 /SINGLE BASE	0.25	0.74	298
1087S1	JA2 /DOUBLE BASE	0.25	0.724	340
10107S1	JA2 /DOUBLE BASE	0.25	0.580	330
10157S1	M30/TRIPLE BASE	0.25	0.64	321
10167S2	M30/TRIPLE BASE	0.25	0.486	316
10157S2	XM39/NITRAMINE	0.25	0.624	316
10167S1	XM39/NITRAMINE	0.25	0.611	314

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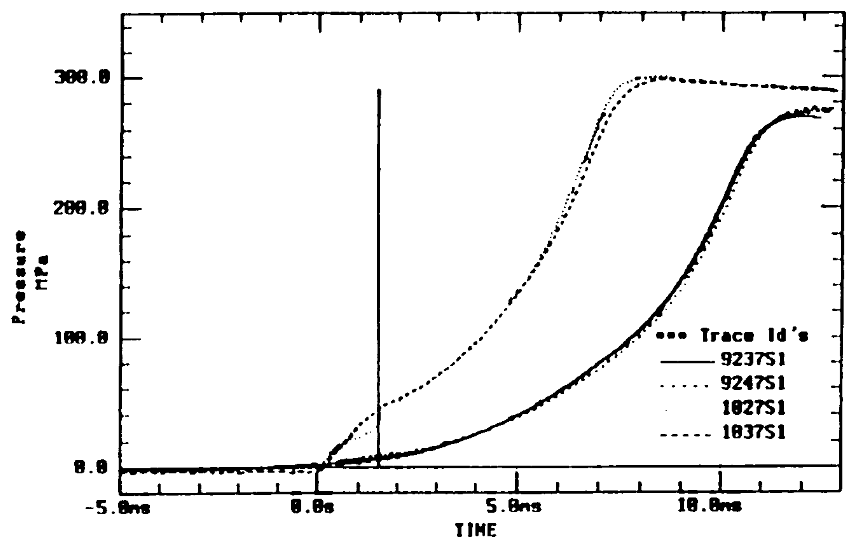
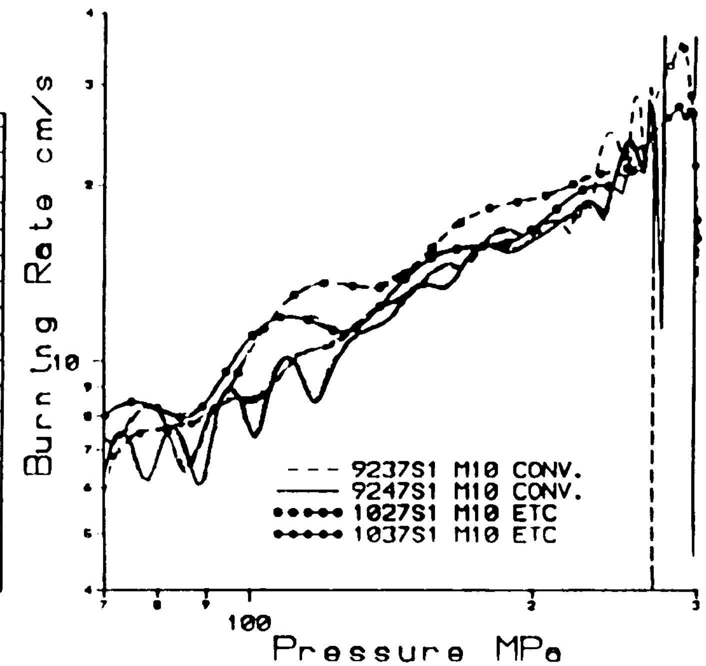
RESULTS

M10 Pressure vs. time and Burn-Rate vs. Pressure



M10 Pressure vs. time



M10 Burn-Rate vs. Pressure

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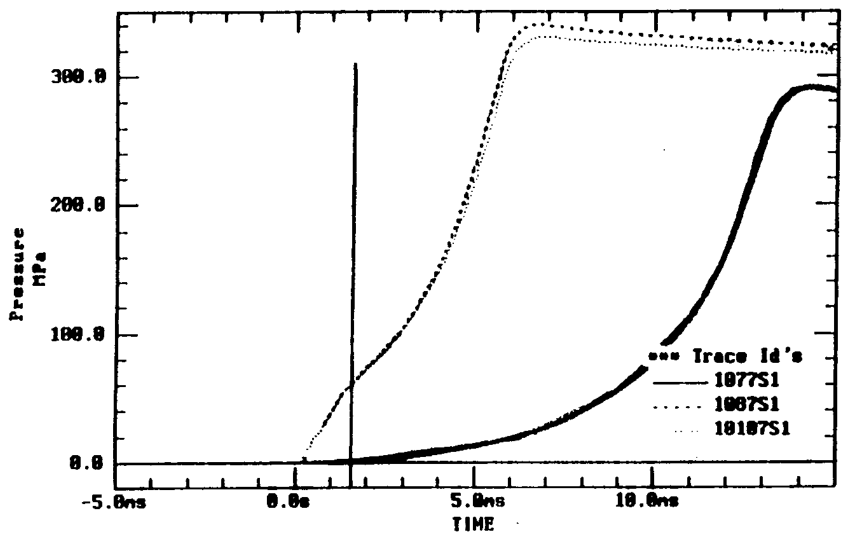
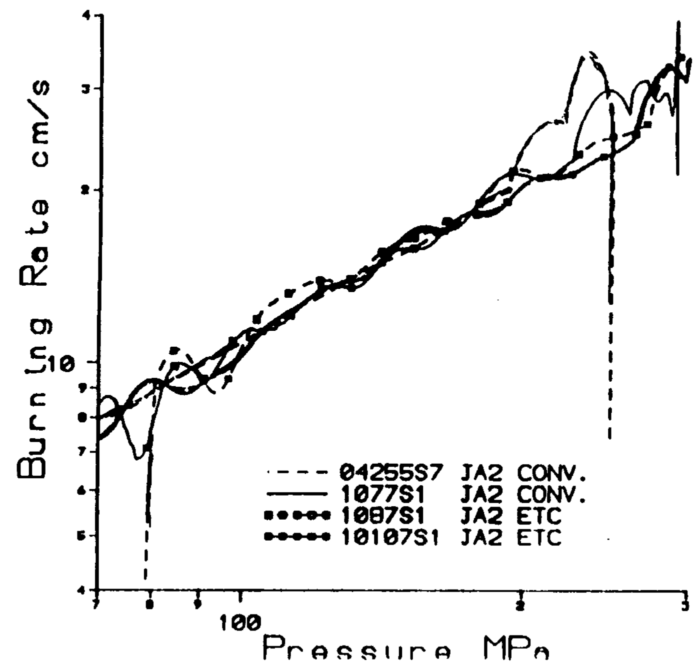
RESULTS

JA2 Pressure vs. time and Burn-Rate vs. Pressure



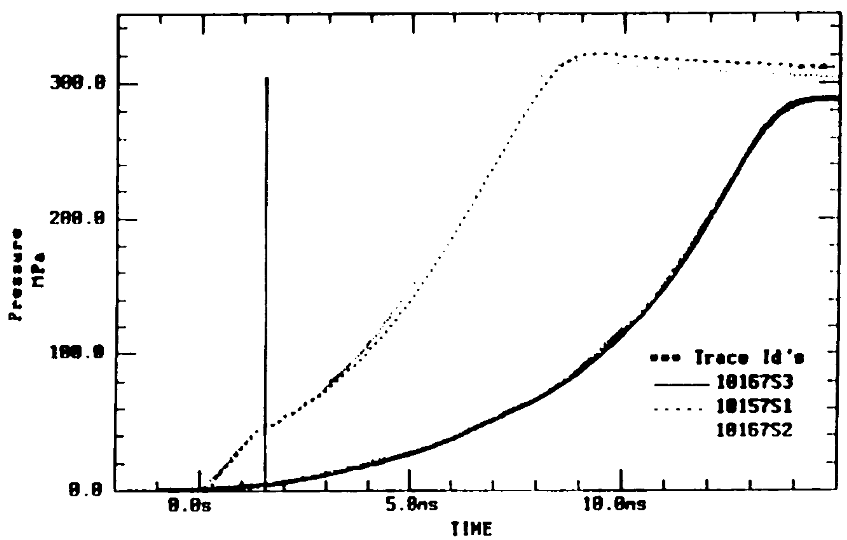
JA2 Pressure vs. time



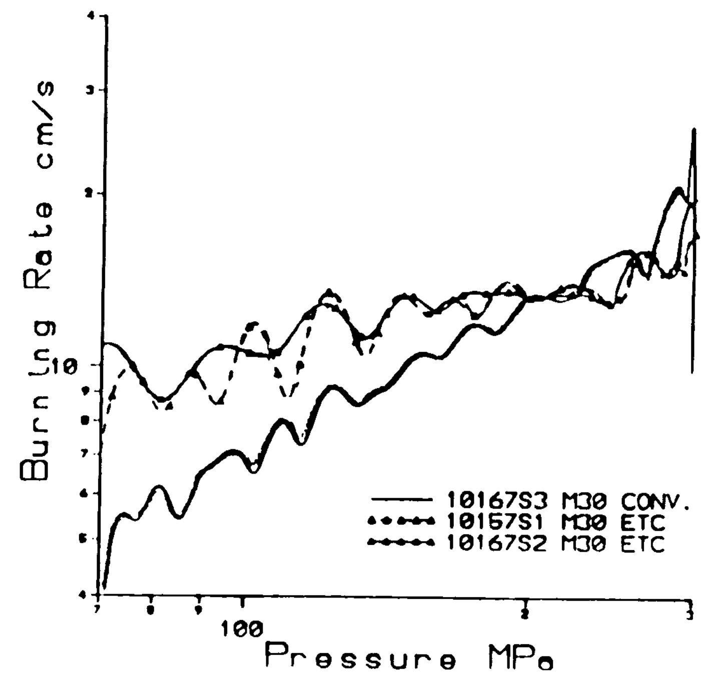
JA2 Burn-Rate vs. Pressure

RESULTS

M30 Pressure vs. time and Burn-Rate vs. Pressure



M30 Pressure vs. time



M30 Burn- Rate vs. Pressure

RESULTS

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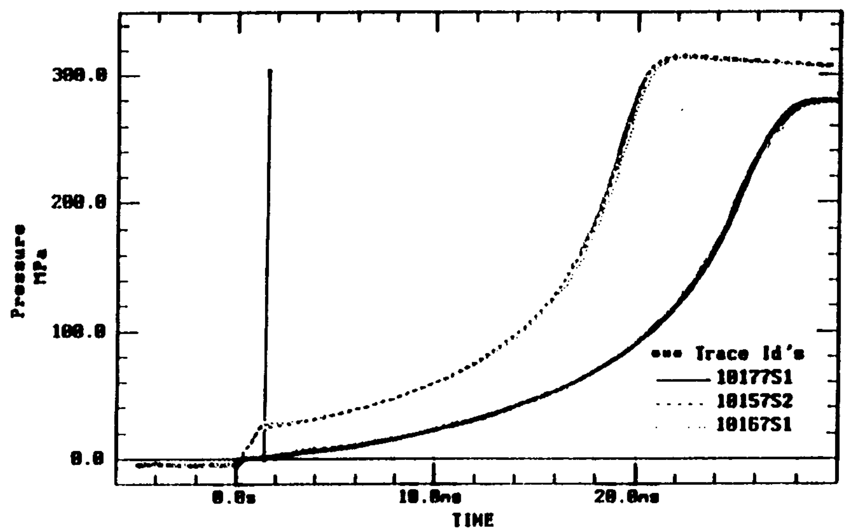
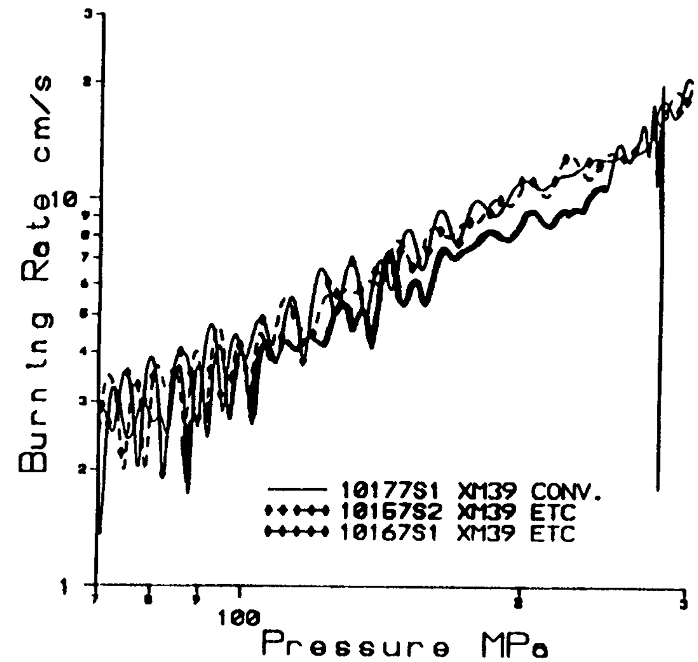
XM39 Pressure vs. time and Burn-Rate vs. Pressure





XM39 Pressure vs. time

XM39 Burn-Rate vs. Pressure

BURN-RATE ANALYSIS

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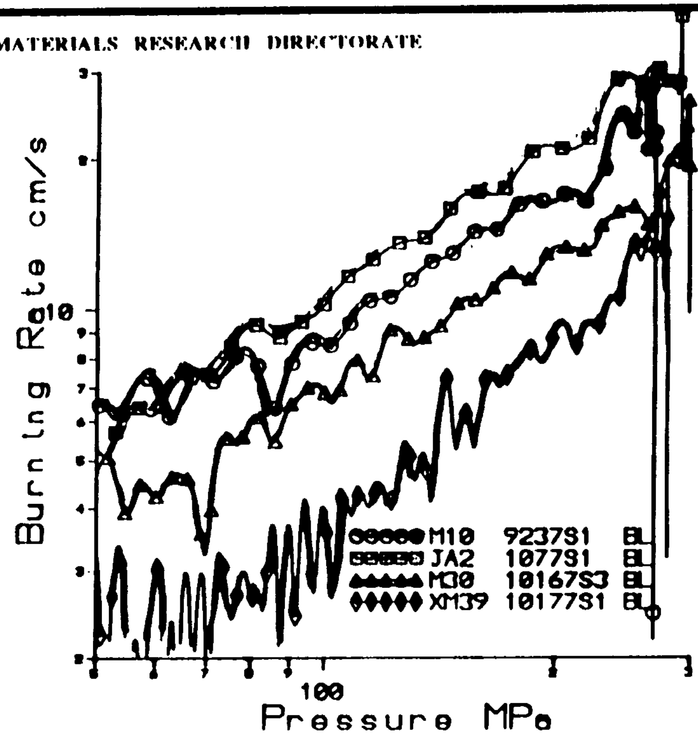

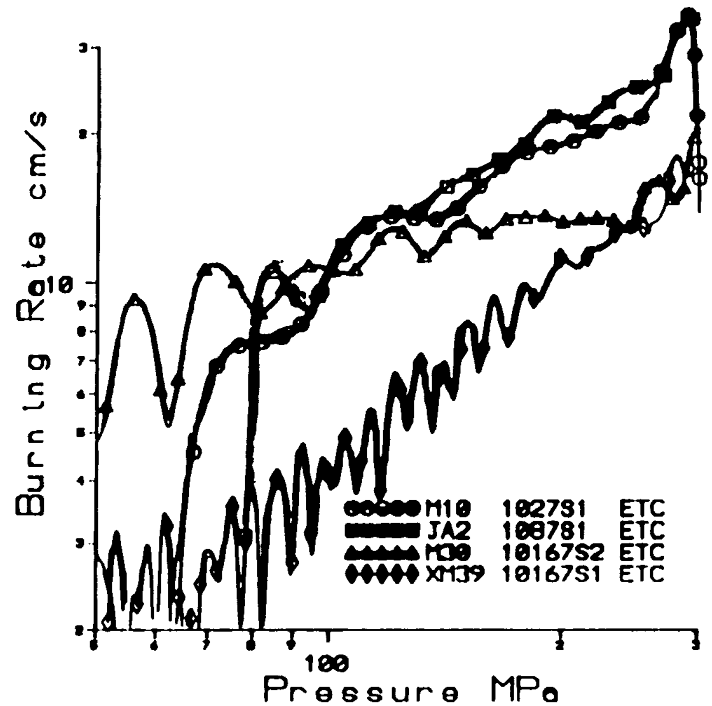

M10,JA2.,M30, XM39 base-lines burn-rates ***M10,JA2.,M30, XM39 ETC burn rates***

SUMMARY

- ***Burn-rate increase observed on single, triple and nitramine base samples tested.***

- ***ETC and base-line burn-rate percent differences between 100 MPa and 220 MPa :***

  a) 17% for M10
  b) 4% for JA2
  c) 33% for M30
  d) 31% for XM39

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CONCLUSIONS

- *The plasma injection modified the burn-rate on the M30 sample significantly between 70 MPa and 150 MPa*

- *The M10,JA2 and XM39 burn-rates had an uniform response to the plasma injection along the 70 MPa to 300 MPa range*

- *The modified capillary plasma injector (L/D=26), seems to improve the transfer of electrical energy into the propellant ignition-combustion processes, and to decrease oscillations on pressure and deduced burn-rates*

Future ARL Research in ETC

ABERDEEN PROVING GROUND

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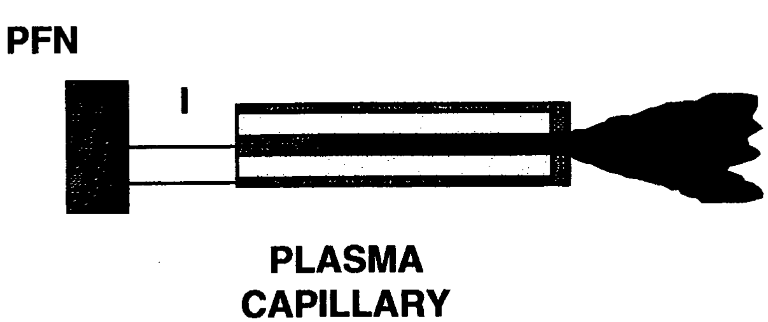
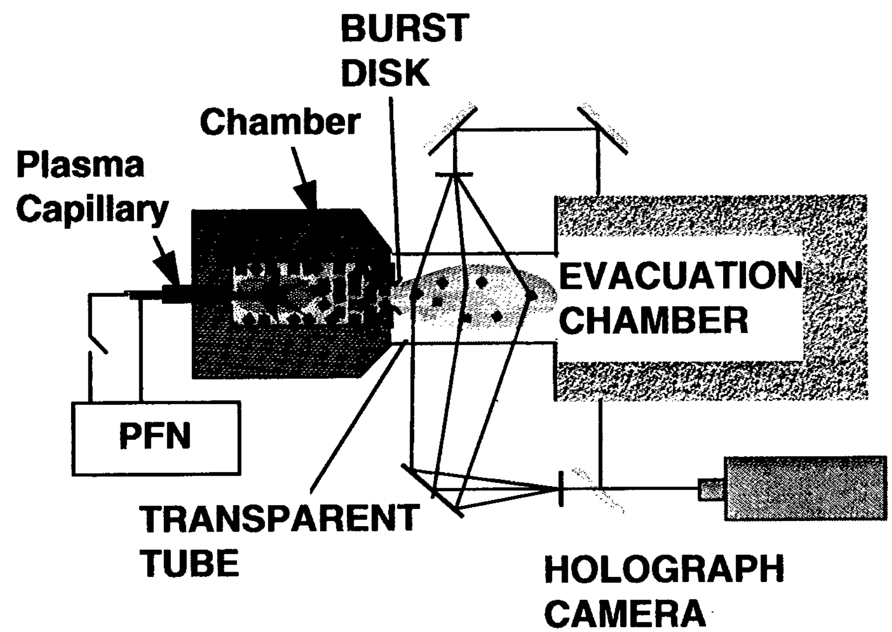


Radiation Transport Code
- spectral output from plasma



Blow-out chamber
-holograph of extinguished products
- chemical & physical analysis of extinguished grains

ETC Ffforts At ISL

&

Closed Chamber Experiments

Dieter Hensel
Pascale Lehmann
Karl Darée
Klaus Zimmermann
Dietrich Grune
Hans-Heinrich Licht
Emil Spahn

Electric and electric-chemical guns

(ISL: 11 %)

Electromagnetic (EM) railgun

(75 %)

PEGASUS: 10 MJ , 50 mm , Nov. 1997
3 MJ , 30 mm

Electromagnetic (EM) coilgun

(5 %)

20 mm , 8 stages , 10 kJ/stage

Electrothermal (ET) gun
Electrothermal-chemical (ETC) gun

(20 %)

12 mm , 20 mm , 60 mm , 100 - 500 kJ

Research in the area of pulse power

a) Switching component

Semi-conductors:

- *Increase of the current rate (dI/dt): 10 kA/μs*
- *Increase of blocking voltage: 12 kV*
- *Increase of the passing current: 100 kA*

b) Pulse forming networks

Most promising pulse power

Mid-term (5 - 10 years):
Fast discharge capacitors and supercapacitors

Long-term (10 - 20 years):
High energy density fast discharge capacitors
Superconducting materials applied to pulsed power technology

ISL ACTIVITIES IN THE FIELD OF ETC GUNS

PERIOD	THEORY	EXPERIMENT
1989-1995	Arc models Plasma physics 2D ET Code (abandoned) ETK1 Version A Code comparison ISL/CEA	12 mm ET launcher Study of different geometries and of different working media v_0 up to 2.3 km/s
1996	ETK1 Version C	Closed vessel experiments
1997	ET code developement abandoned (?) Investigation of powder ignition by a plasma	Ignition of propellants by plasmas Experiments in closed vessel and in launchers

1997-	Plasma ignition

Plasma Ignition

- **Objective**
  gain in muzzle kinetic energy (> 30%)
  high projectile velocities
  (120 mm: 1650 m/s ⇒ 1900 m/s)
  kinetic energy > 33 %

- **Method**
  more chemical energy
  loading density > 1 g/cm^3
  electrical energy < 500 kJ

- **Effect**
  controlled reduction of high gas pressures
  controlled ignition
  controlled combustion

- **Problem**
  special (coated) propellant
  consolidated charges
  optimized plasma igniter

ISL research program

- **Closed vessel + plasma burner**

  1. Interaction of plasma and propellant / combustion gases
  2. Law of burning $r = r (p , T)$

- **Electrothermal (ETC) gun,**
  12 mm, 20 mm, 60 mm , ***100 - 500 kJ,*** $p_{max} = 450$ ***Pa***

  1. Firing with conventional ignition and with plasma ignition
  2. Internal ballistics of coated propellant + plasma

- **120 mm firing simulator**

  1. Plasma igniter + inert material
  2. Plasma igniter + coated propellant

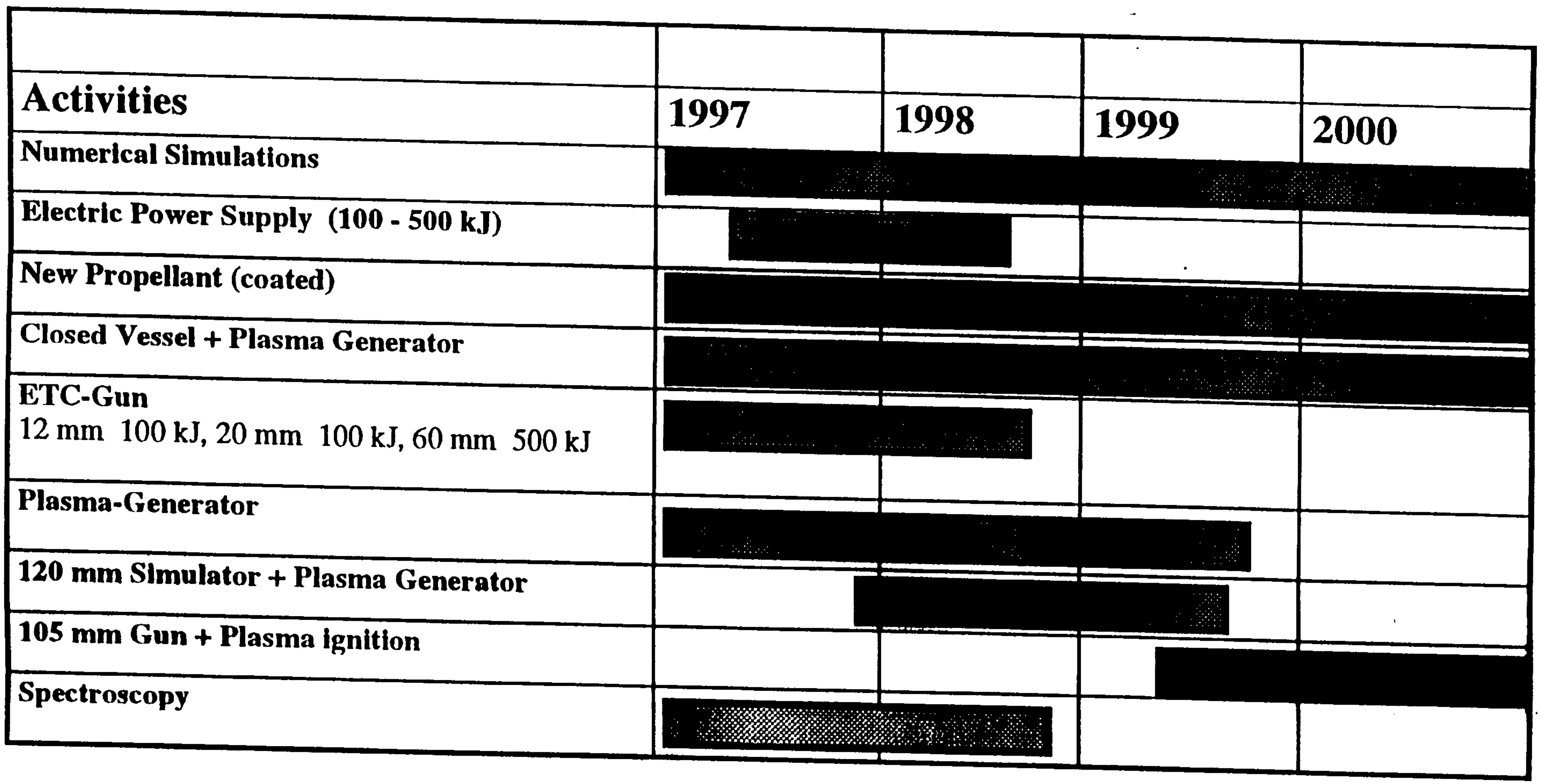
- **105 mm experimental ETC gun**

  1. Successful firing: plasma igniter + coated propellant

- **Development of „special“ propellant**

- **Spetroscope**

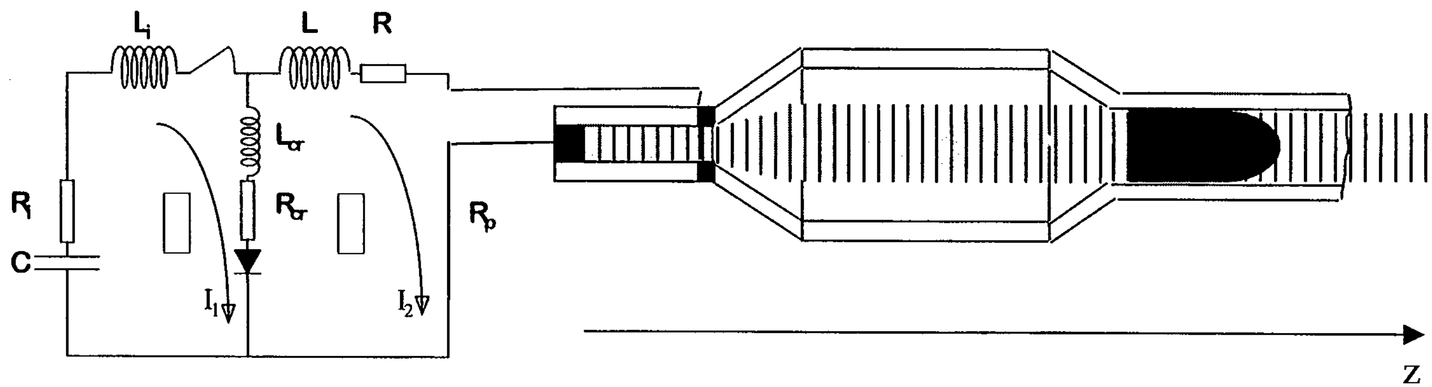
  1. Plasma qualities (radiation)



ISL ETC Program Overview **01.01.1998**

ETK1D - Computation of:

1. Circuit 2. Arc 3. Interior Ballistics



Spatial resolution in axial direction ⟶

Radial averages for temperature, density, pressure and flow velocity

1. Gas dynamics

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial z}=0$$

$$U=\begin{pmatrix}\rho\\ \rho v\\ \varepsilon\end{pmatrix},\qquad F=\begin{pmatrix}\rho v\\ \rho v^2\\ (\varepsilon+p)v\end{pmatrix},\qquad \varepsilon=\rho e+1/2\rho v^2$$

2. Ohmic heating

$$\frac{\partial e}{\partial t}=\frac{I^2}{\rho\sigma F^2},$$

$\sigma(z,t)$= el. conductivity, $F=\pi a^2/4$, $a(z,t)$=arc diameter

3. Radiation loss

$S=E\pi af_S\sigma_{SB}T^4$,

E=emissivity (usually E=1), $\pi af_S(t)$=effective surface

4. Mass flow

Into plasma: $\dot{m}_p=\left[SA_p+c_{pv}(T-T_v)\right]\Big/(h_p-h_v)$,

$h_{p,v}$= enthalpies of plasma and vapour, $c_{pv,vw}$=heat transfer coeffs.

Ablation: $\dot{m}_v=\left[S(1-A_p)(1-A_v)A_w+c_{vw}T_v\right]\Big/\Delta h$,

Δh= enthalpy of evaporation (decomposition, depolymerization)

Unknown parameters:

f_S : Effective arc surface

must be guessed as a function of time and in dependence of the nature of the working medium (gun powder); f_S = const. is a good approximation in most cases.

$c_{pv,vw}$: Heat transfer coefficients for conductive-convective transfer

c_{pv}=0 can always be assumed (transport between plasma and vapour by radiation only)
c_{vw} can be obtained from closed vessel experiments with inert powders

T_v : Vapour temperature

T_v has little influence. It can be assumed constant ($T_v \cong 3000$ K)

Computed and tabulated values:

1. With the ISL-SLYPIG subroutine library

    Equations of state $p(\rho,T)$, $e(\rho,T)$

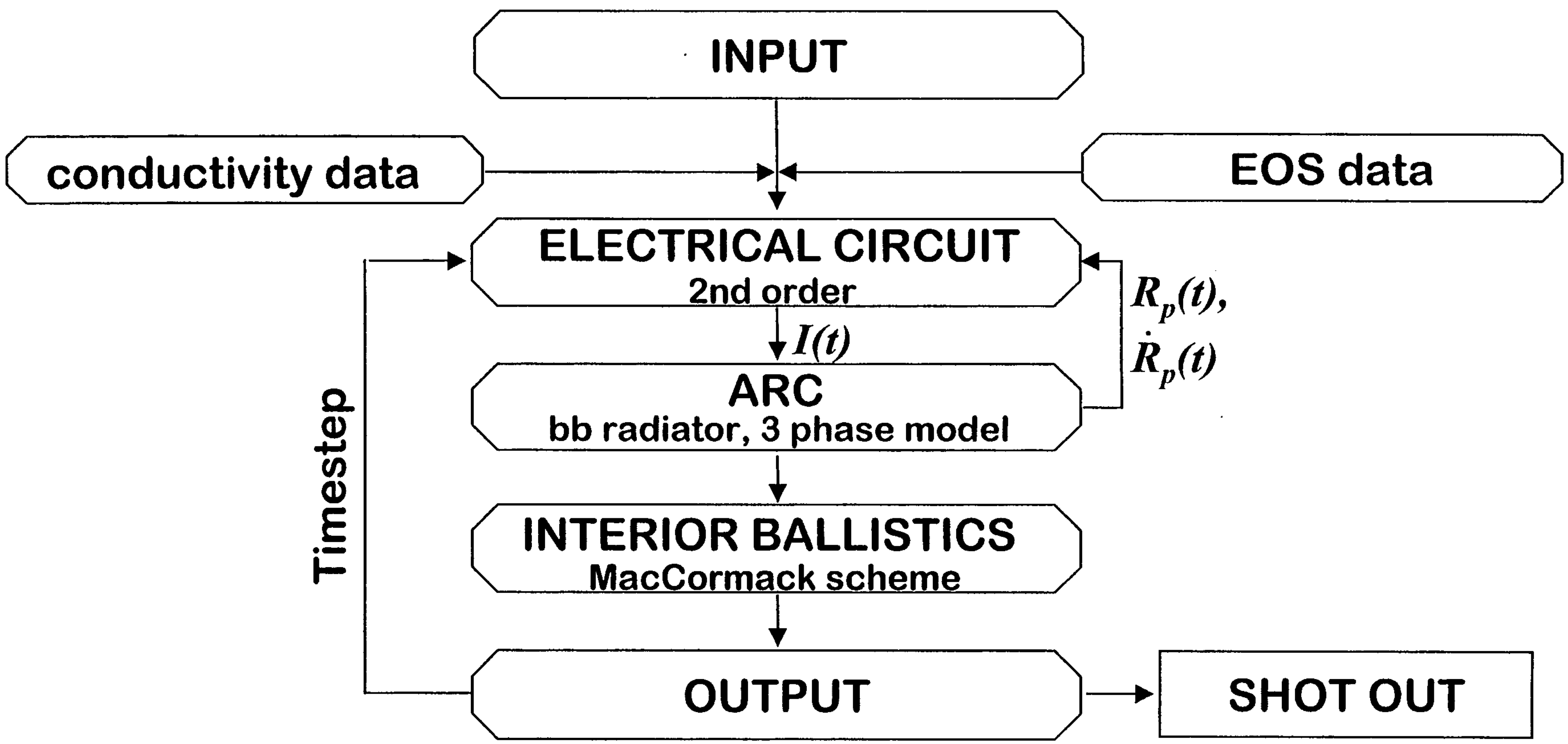
    Electrical conductivity $\sigma(\rho,T)$

    Rosseland opacities for plasma, vapour and condensed matter; emission spectrum of the arc, spectral absorption in vapour and plasma, absorption coefficients $A_v(p,T)$ and $A_w(p,T)$

2. With radially resolving arc model ARCETK

    Plasma self-absorption $A_p(p,T)$,
    plasma emission temperature $T_r=T(1-A_p)^{1/4}$

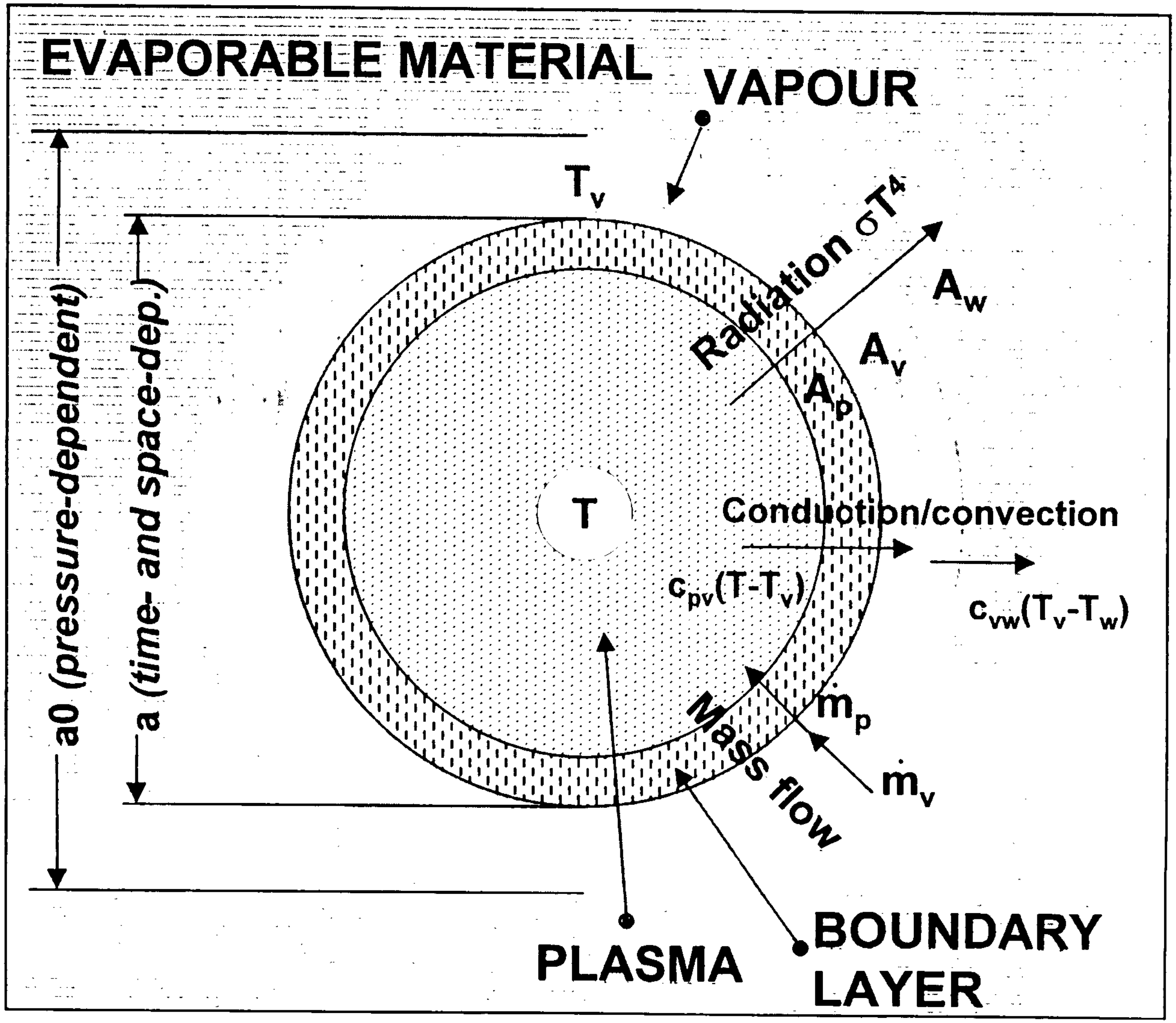
STRUCTURE OF ETK1D



ARC MODEL OF ETK1D

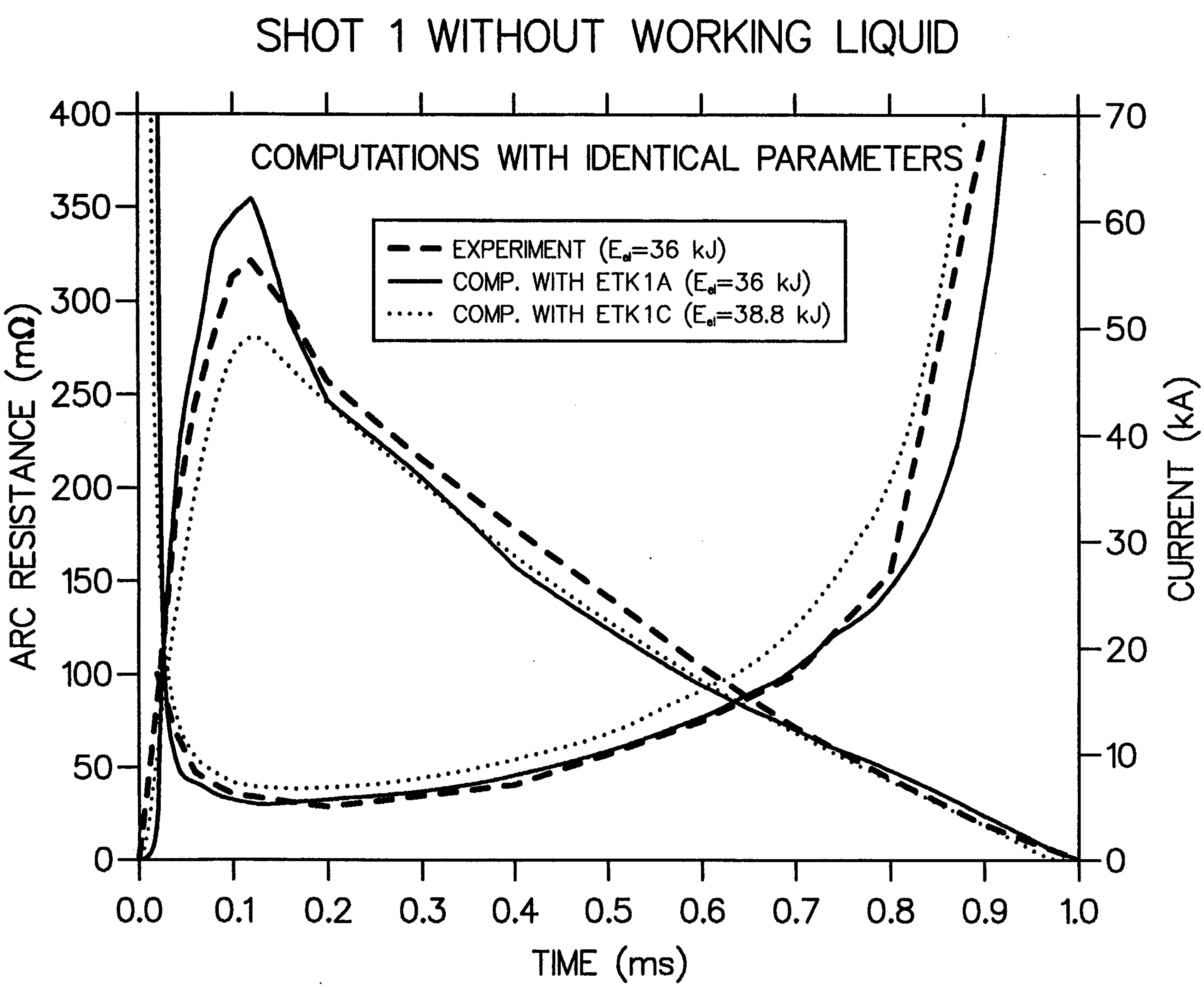
THREE PHASE MODEL

Blackbody radiator with self-absorption in boundary layer

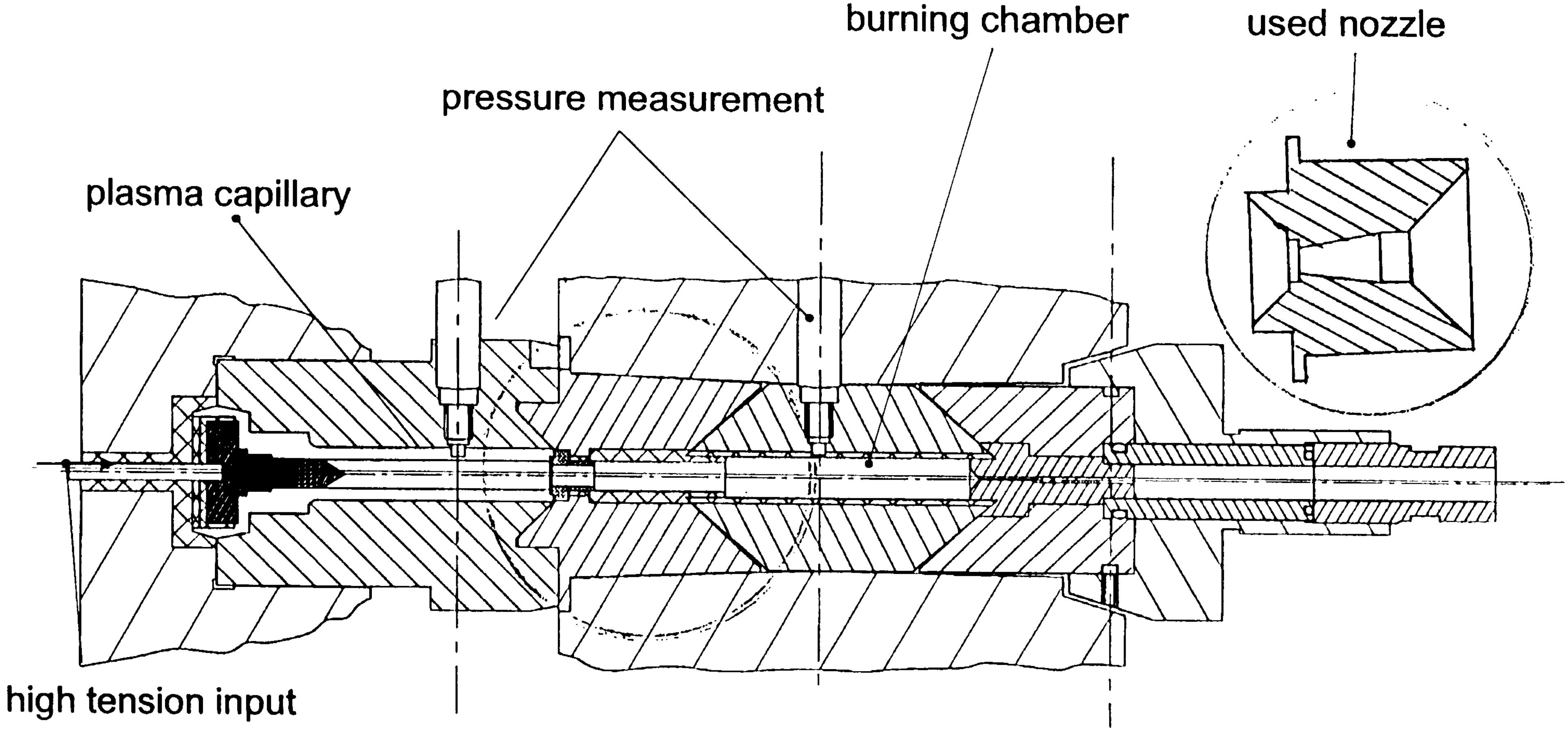


DEA-G-1060 German/US Workshop

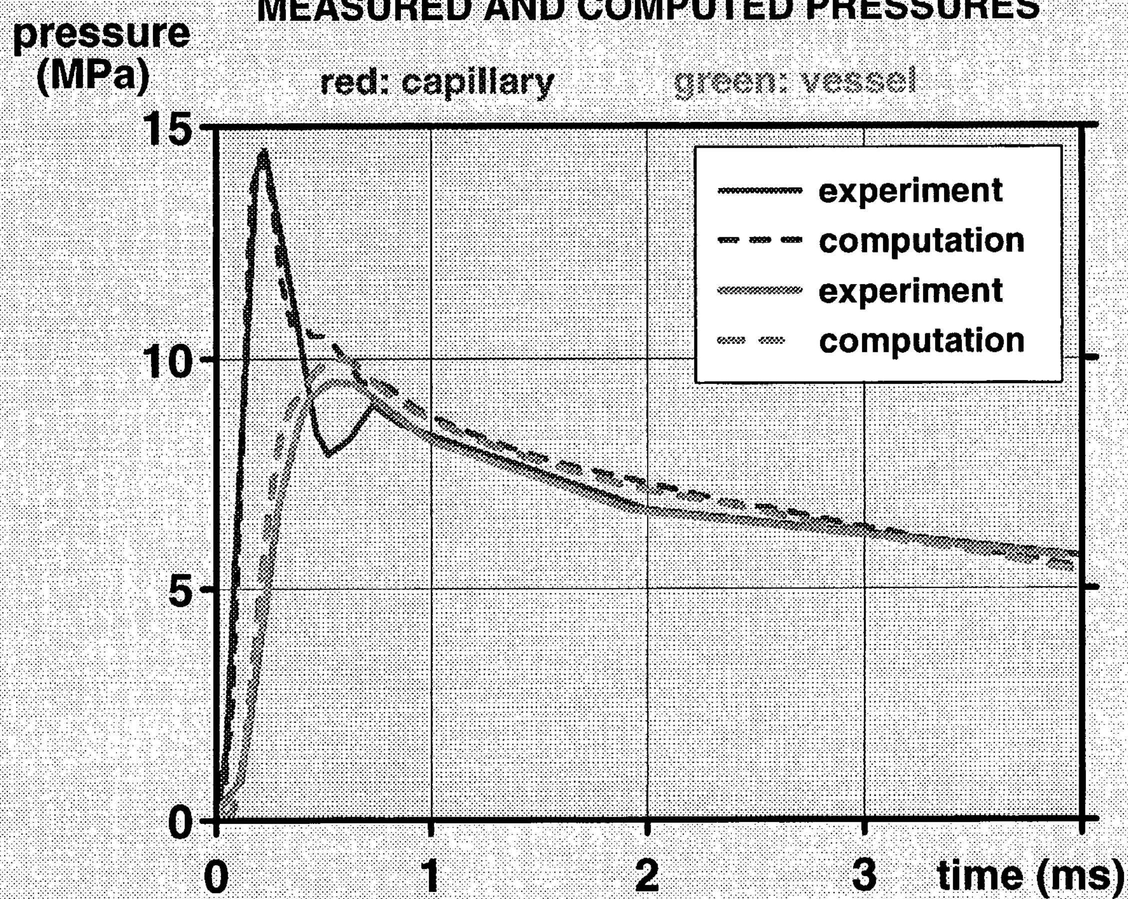
27-28/1/98


SHOT 1 WITHOUT WORKING LIQUID
COMPUTATIONS WITH IDENTICAL PARAMETERS
EXPERIMENT (E_{el}=36 kJ)
COMP. WITH ETK1A (E_{el}=36 kJ)
COMP. WITH ETK1C (E_{el}=38.8 kJ)
ARC RESISTANCE (mΩ)
CURRENT (kA)
TIME (ms)
400
350
300
250
200
150
100
50
0
70
60
50
40
30
20
10
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

SKETCH OF THE PLASMA PRESSURE BOMB



MEASURED AND COMPUTED PRESSURES



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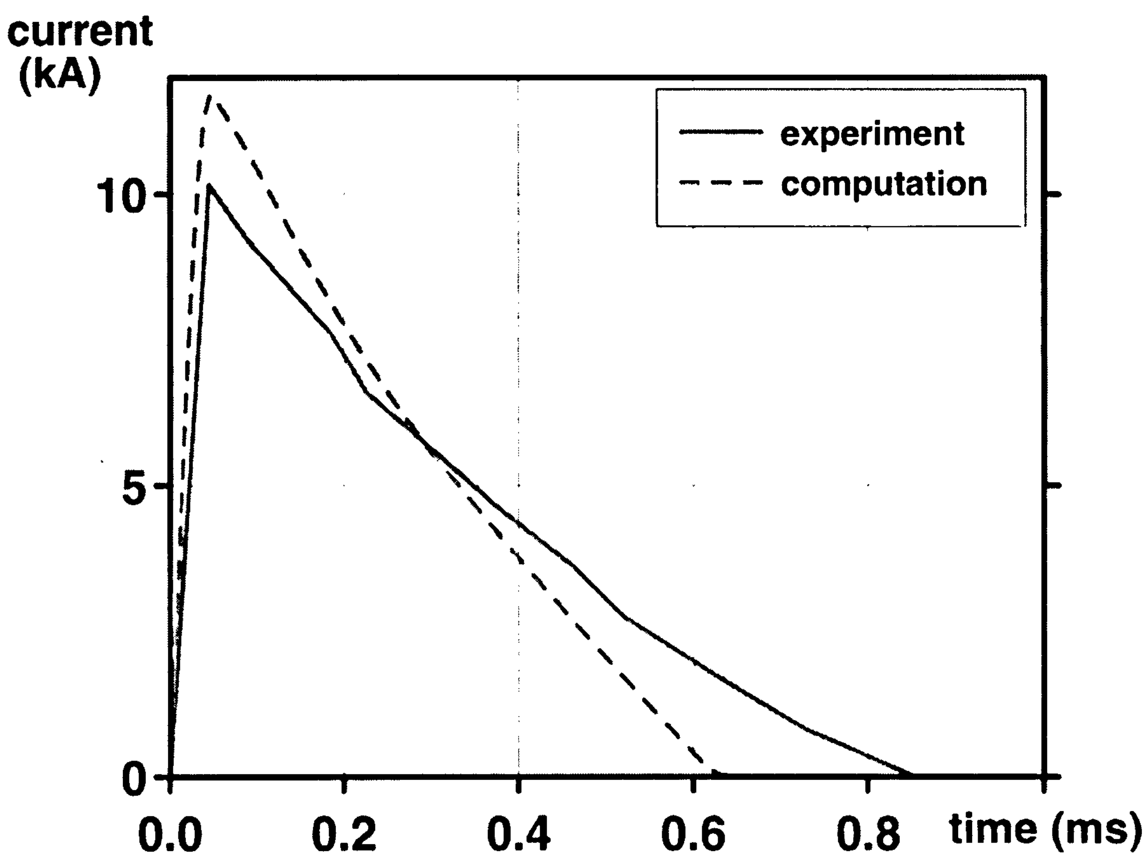
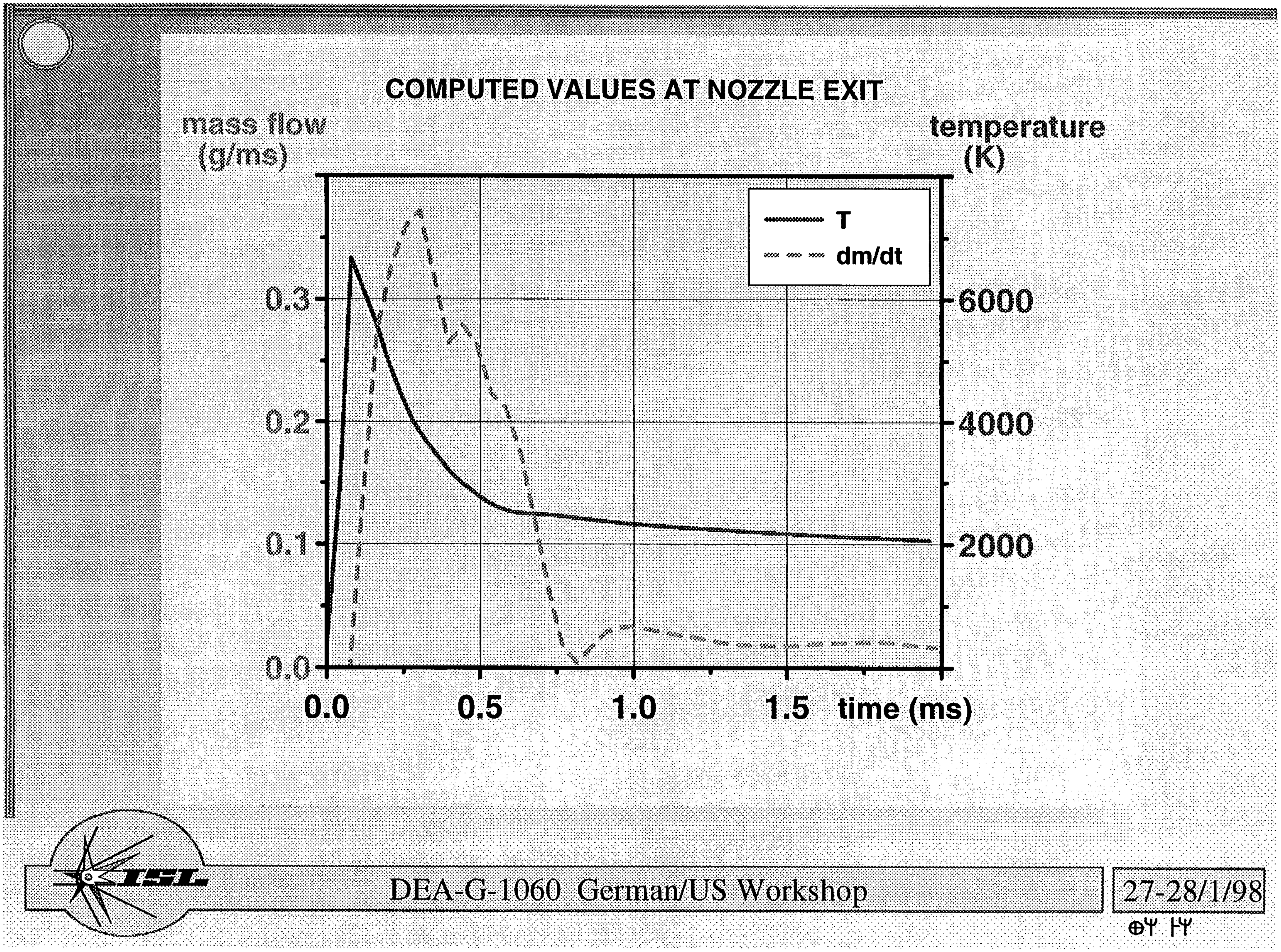
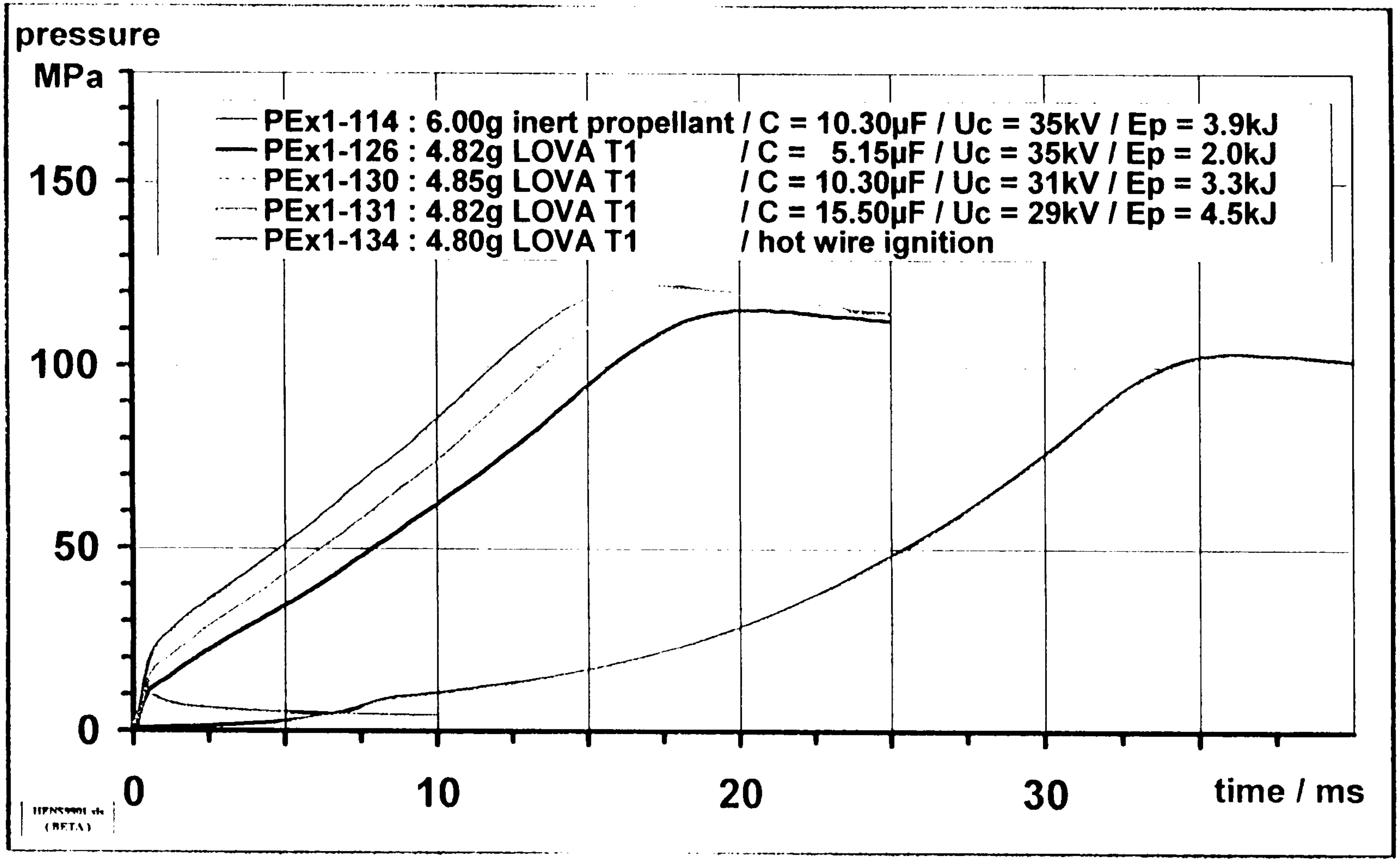
27-28/1/98

MEASURED AND COMPUTED CURRENT



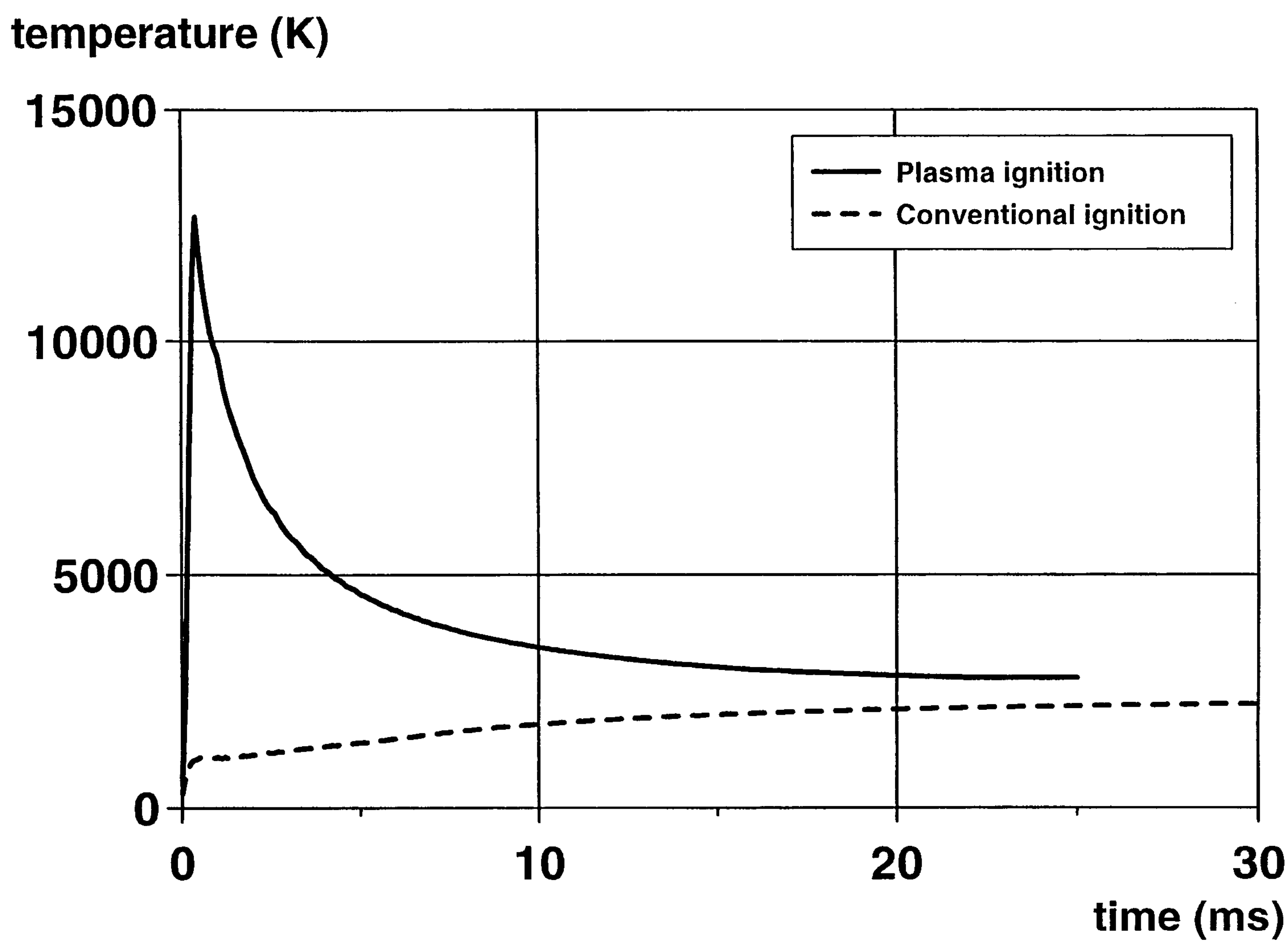

COMPUTED VALUES AT NOZZLE EXIT
mass flow (g/ms)
temperature (K)
T
dm/dt
0.0
0.1
0.2
0.3
2000
4000
6000
0.0
0.5
1.0
1.5
time (ms)
DEA-G-1060 German/US Workshop
27-28/1/98

COMBUSTION BY PLASMA IGNITION

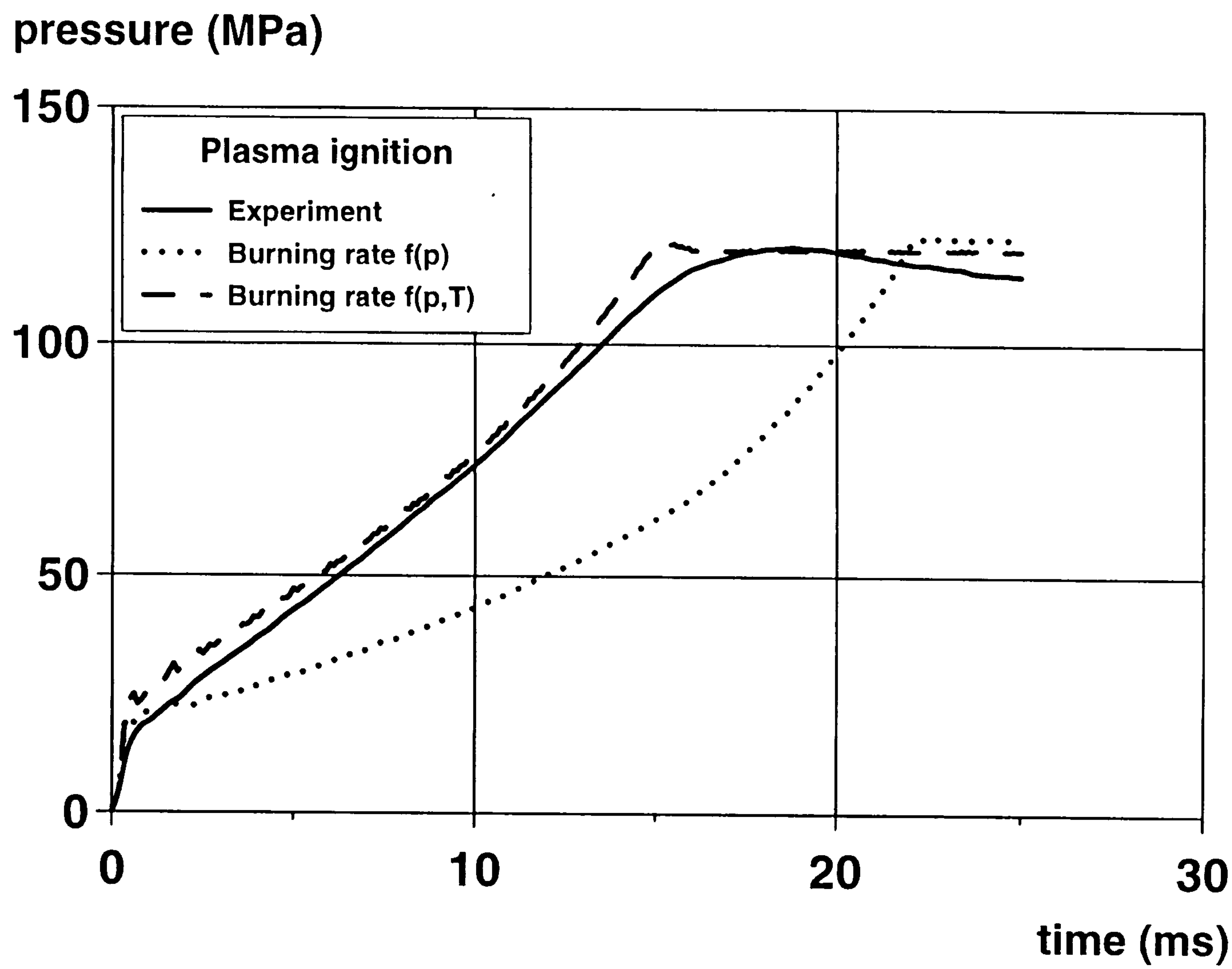


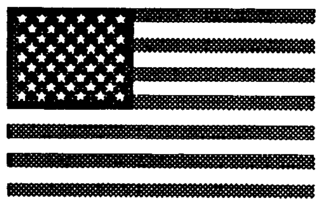
DEA-G-1060 German/US Workshop

Jan 1998

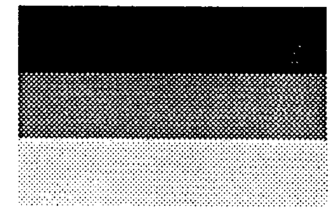

temperature (K)
15000
10000
5000
0
0
10
20
30
time (ms)
Plasma ignition
Conventional ignition

$$r(p,T) = e^{\frac{T - T_{EX}}{T_{EX}}} \cdot \beta \cdot p^{\alpha}, \quad T > T_{EX}$$





Plasma Radiative and Convective Interactions With Propellant Beds



Michael Nusca & Kevin White

Weapons & Materials Research Directorate
Army Research Laboratory, Aberdeen Proving Ground, MD

DEA-G-1060
German/US Workshop on
Electrothermal-Chemical Gun Propulsion
27-28 January 1998, Aberdeen Proving Ground

PROPOSED QUESTIONS

DEA 1060, 27-28 January 1998

1. What kind of theoretical considerations concerning the plasma/propellant interaction have been performed?

2. Do you have appropriate modeling tools to calculate ETC effects in comparison to conventional ignition and how do they work (detailed energy release in space and time or simply lumped parameters, energy added globally as heat)?

3. Are radiation effects taken into account in these models?

4. Do you have measured time and wavelength resolved spectra of the plasma and/or burning propellant?

5. What type of experimental setup has been considered to be promising in studying the ETC effect?

6. Which closed vessel experiments have been performed in the last five years to examine the interaction between plasma and burning propellant?
    - types of closed vessel arrangements
    - pressure range of experiments
    - loading density and type(s) of propellant
    - results of different setups (load configurations) and possible explanation of behavior

7. Which type(s) of power supply has been used? single pulse, sequential triggering

8. Which type of energy converter has been used (e.g. piccolo-type, multi-electrode)

9. Which type of firing experiments have been performed during the last five years?
    - powder charge arrangements and type of energy release
    - caliber, barrel length, chamber volume
    - results, especially muzzle velocity and ballistic efficiency

Outline

- Background
- Optical Properties of Propellants
- Energy Deposition Simulations
  - Radiative Heating, *LightTools*
  Conventional & Plasma Igniter
  - Convective Heating, NGEN
- Experimental Technique
  Convective & Radiative Heat Flux
- Conclusions
- Plans

Background

- Propellant ignition by plasmas
  - short reproducible ignition delays
- Reduced propelling charge temperature sensitivity by plasmas
  - observed in small & large caliber gun firings
- Propellant combustion control by plasmas
  - observed in some propellants but not others

Does plasma radiation play a role in these observations? Does convective heating by a plasma differ from convective heating by combustion products?

Possible Mechanisms

- Chemical
  - plasma ion/radical-propellant interaction
  - photolysis from plasma uv
- Mechanical
  - propellant erosion from plasma flow
  - propellant fracturing/cracking
- Thermal
  - in-depth heating due to plasma radiation
    burn rate, 0.2-0.5%/K
  - sub surface reactions

Electrothermal Chemical Gun

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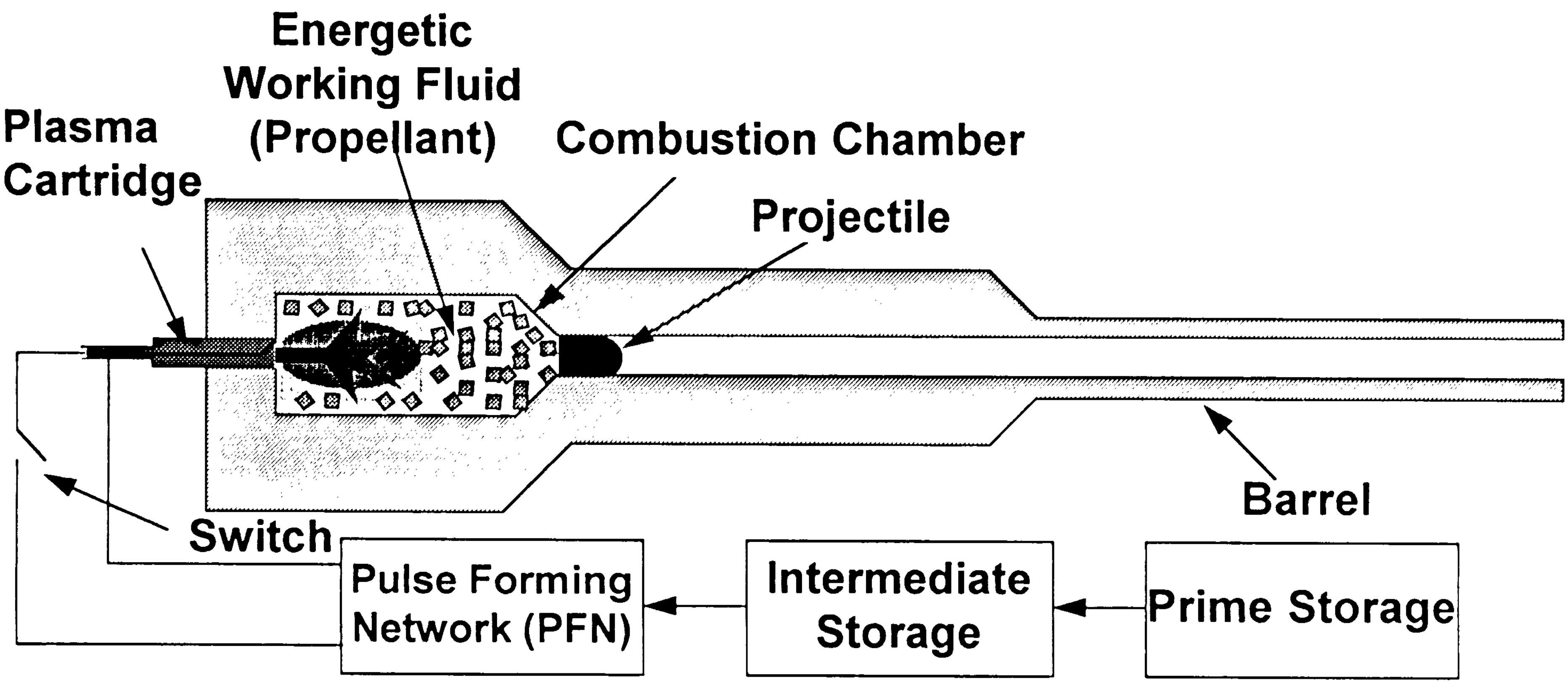

Heat Flux, W/m^2

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Convective

Gelpern-Einstein Correlation

$Q_c = h_c (T - T_p)$ W/m^2

$h_c = 0.4(k\rho u)^{2/3}(c/D_p\mu)^{1/3}$

or

$h_c = 0.4(k/D_p)\, P_r^{1/3}\, R_e^{2/3}$

$P_r = \mu c/k \quad R_e = \rho u D_p/\mu$

unsubscripted terms are for plasma/gas mixture

Radiation

$Q_r = \epsilon\sigma(T^4 - T_p^4)$

ϵ = emissivity

$\sigma = 5.67\times10^{-8}$ W/m^2K^4

$c = 1.61\times10^3$ J/kgK (N_2@ 2800K)

$k = 0.3$ W/mK (SOREQ)

(N_2 @ 3500K, 0.2 W/mK)

$\mu = 2.6\times10^{-5}$ kg/ms (SOREQ)

(N_2 @ 2800K, 8.2×10^{-5}kg/ms)

$D_p = 1\times10^{-2}$m

$\rho = 0.1 - 0.5$ kg/m^3 (Powell)

$u = 300 - 2000$ m/s (SOREQ)

Convective, Q_c vs Radiative, Q_r Heat Flux

	Q_c, MW/m^2		Q_r, MW/m^2
	v = 300 m/s	v = 2000 m/s	
T = 5000K	19	70	35
T = 10,000K	40	142	560

Heating Of An Inert Slab

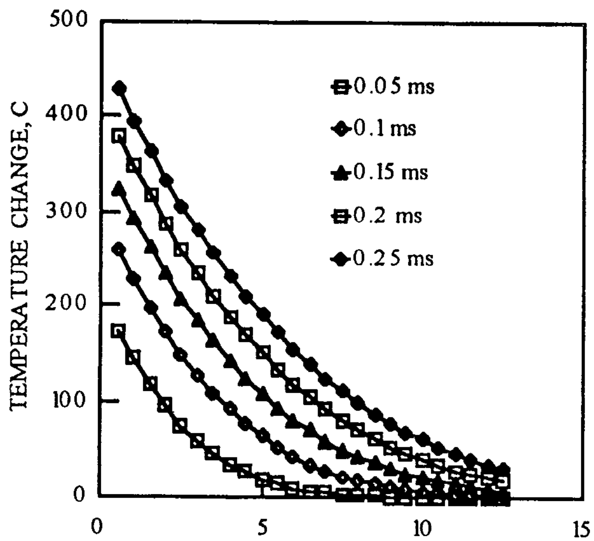
STANDARD IGNITION/COMBUSTION

ABERDEEN PROVING GROUND

WEAPONS & MATERIALS RESEARCH DIRECTORATE

CONVECTIVE

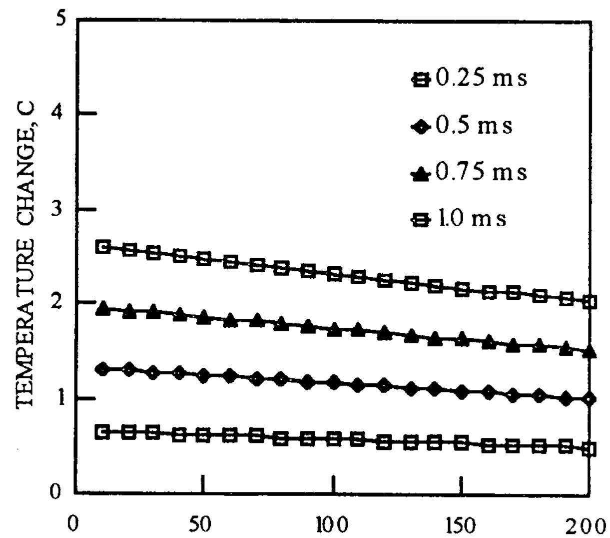
CONVECTIVE HEATING, Q = 2100 W/cm^2



Convective heating yields rapid surface heating.

RADIATIVE

n = 13 cm^-1, Q = 450 W/cm^2, (T = 3,000K)



Flame radiation heating insignificant.

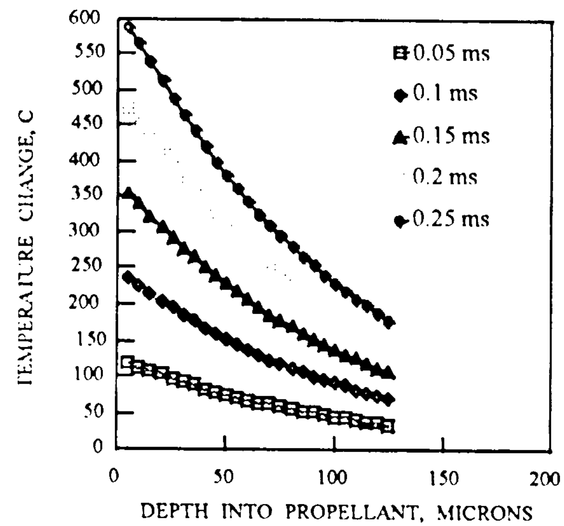
Heating Of An Inert Slab
PLASMA RADIATION

ABERDEEN PROVING GROUND

WEAPONS & MATERIALS RESEARCH DIRECTORATE

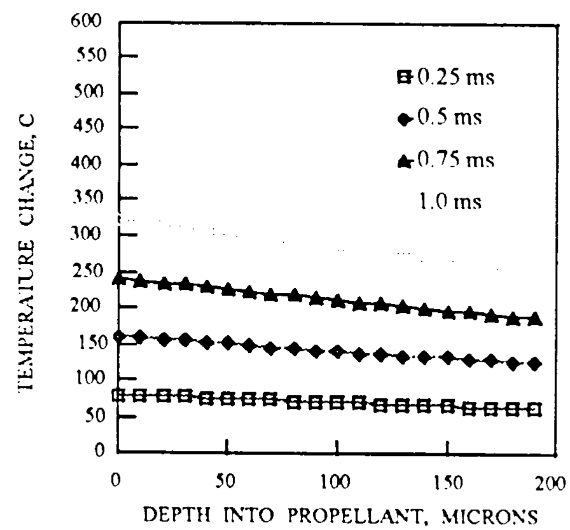
HIGH ABSORPTION COEFFICIENT

n = 100 cm^-1, Q = 56,000 W/cm^2, (T = 10,000K)



LOW ABSORPTION COEFFICIENT

n = 13 cm^-1, Q = 56,000 W/cm^2, (T = 10,000K)



High absorption coefficient results in rapid near-surface heating.

Lower absorption coefficient leads to in-depth heating.

Radiative Heating of a Slab
n = 5, 3 and 1 cm^-1

ABERDEEN PROVING GROUND

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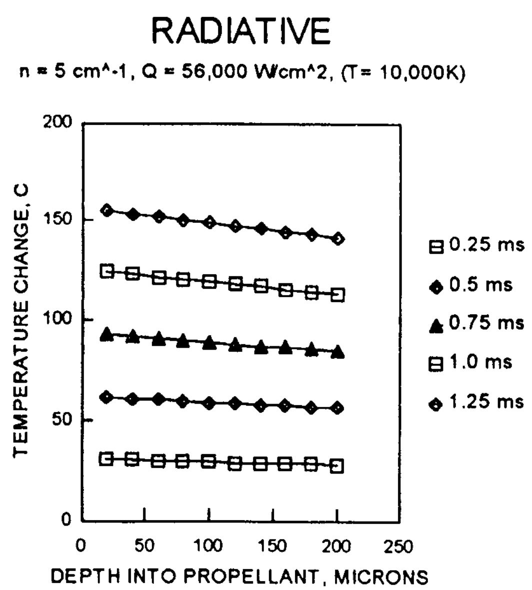
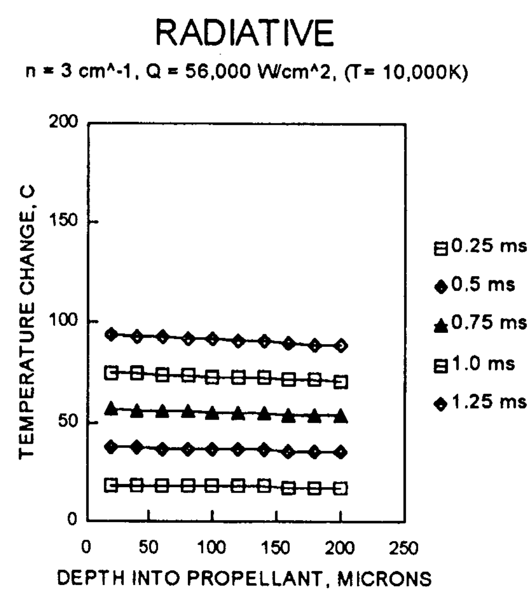
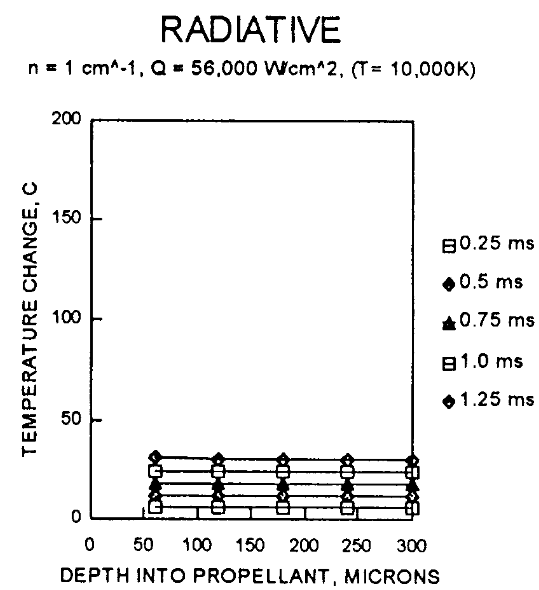
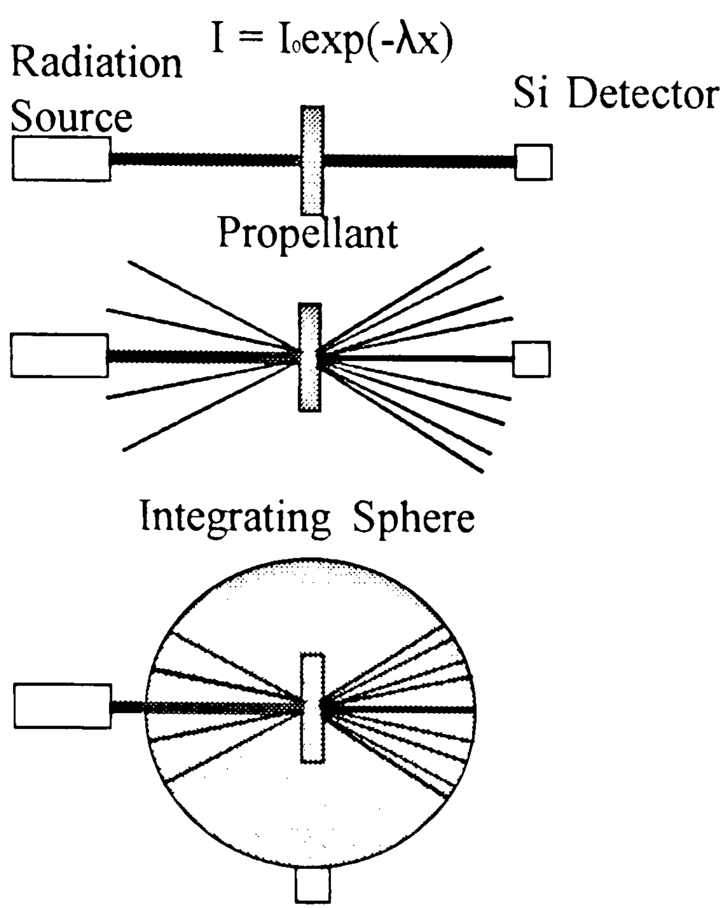
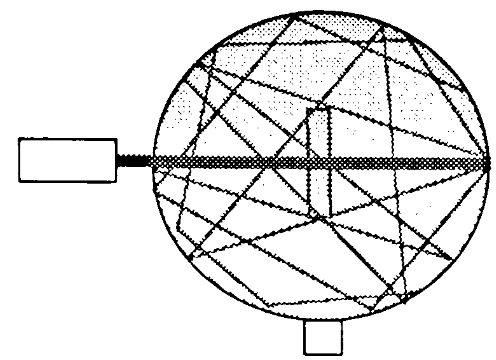


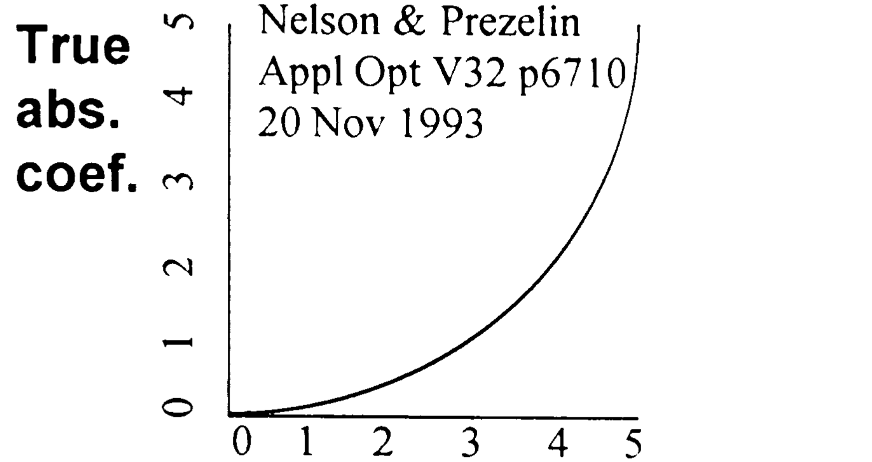




Integrating Sphere Absorption Coefficients







Calibration for Integrating Sphere

ABERDEEN PROVING GROUND

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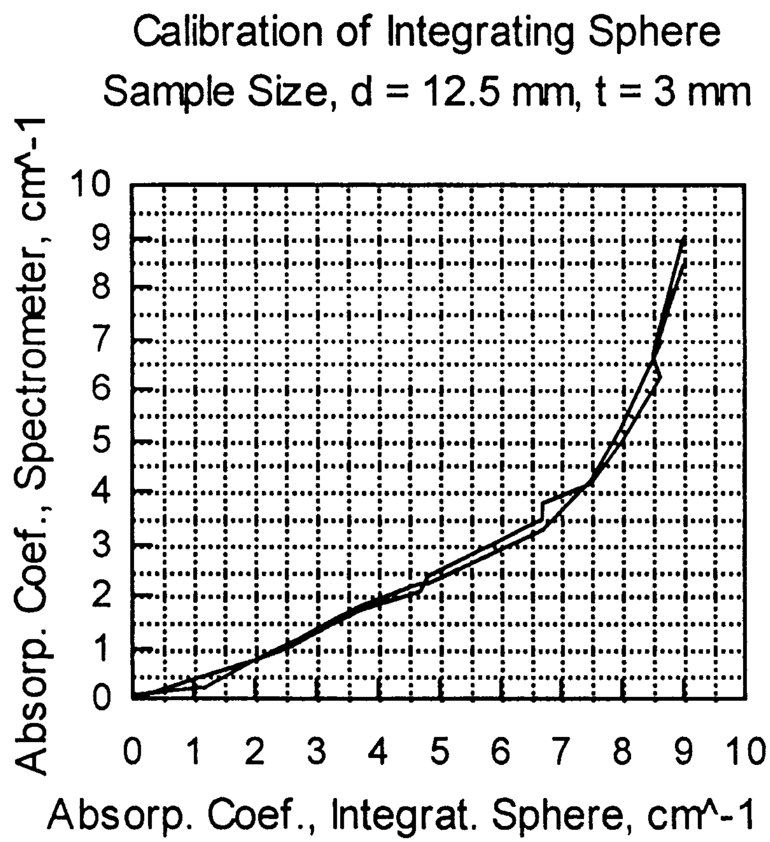

$$AC(SPEC) = 0.094 - 0.311AC + 0.5AC^2 - 0.106AC^3 + 0.00729AC^4$$

Absorption Coefficients Integrating Sphere

ABERDEEN PROVING GROUND

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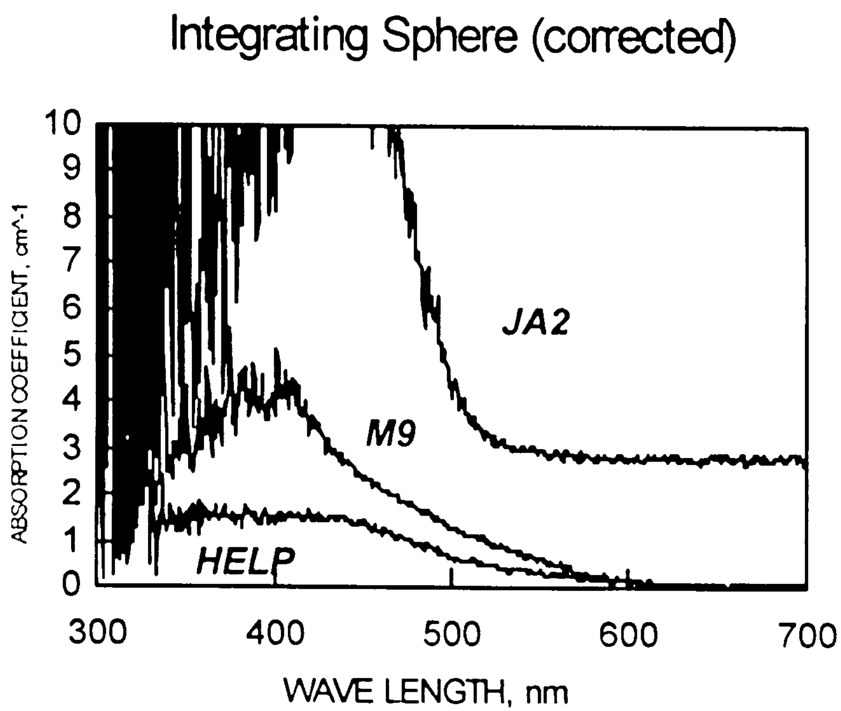

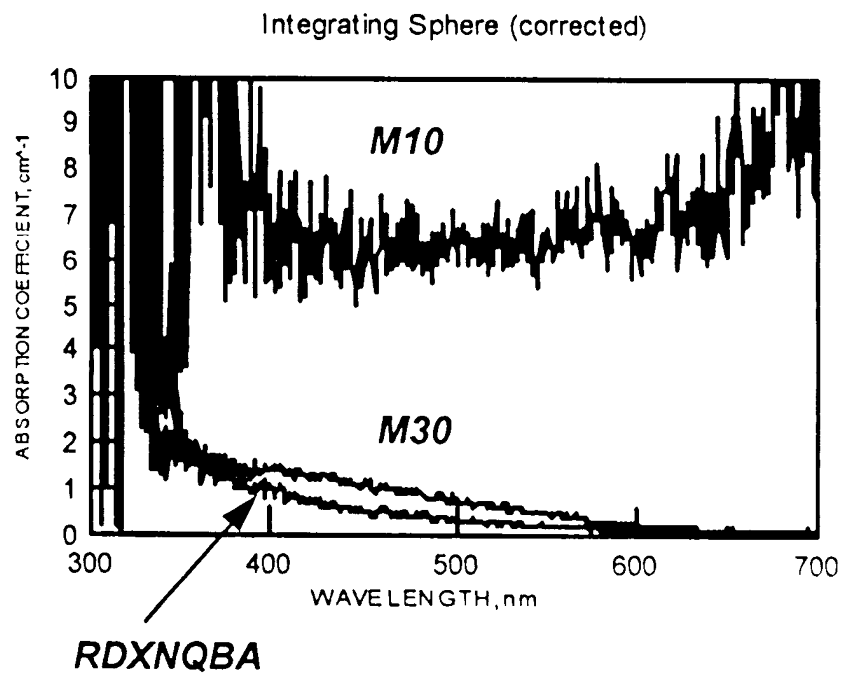

Propellant reflection coefficients must be determined

Plasma Spectra & Propellant Response

ABERDEEN PROVING GROUND

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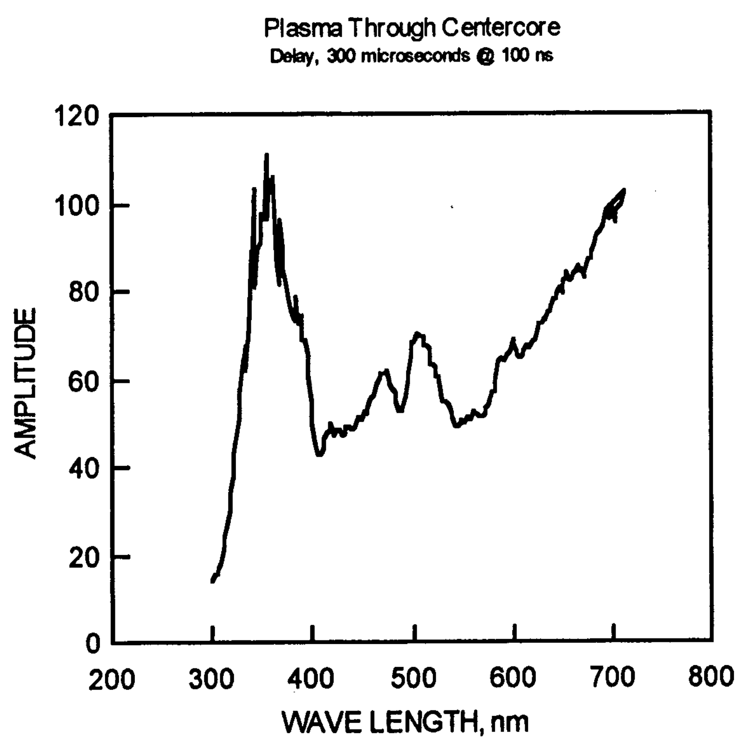

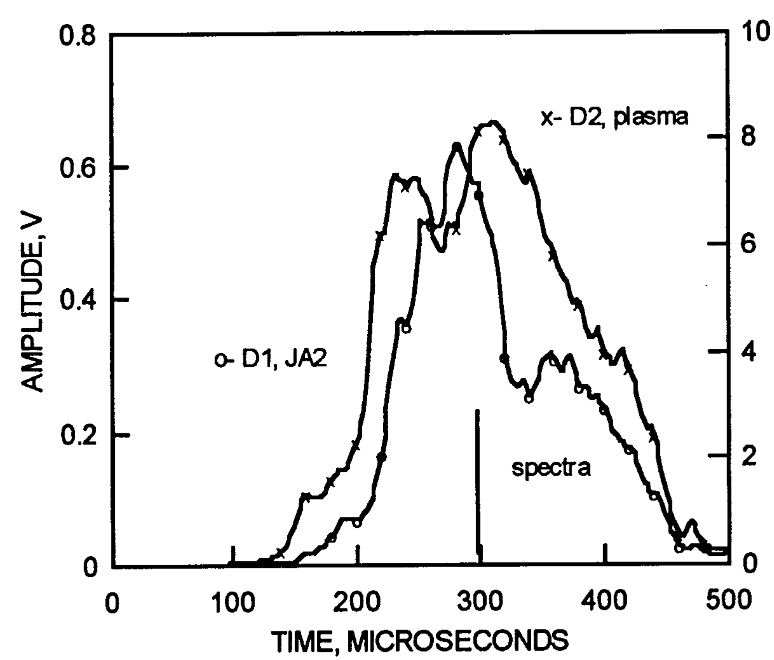

Spectra taken through polyethylene tube

Radiation Transport Calculations

ABERDEEN PROVING GROUND

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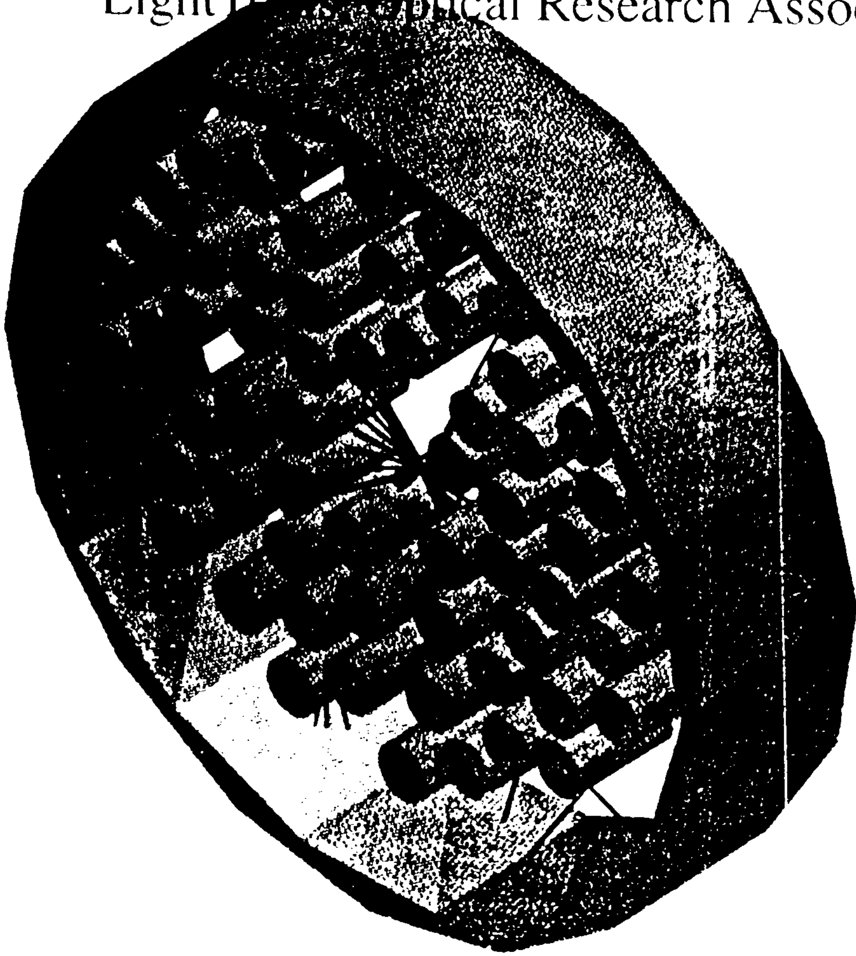
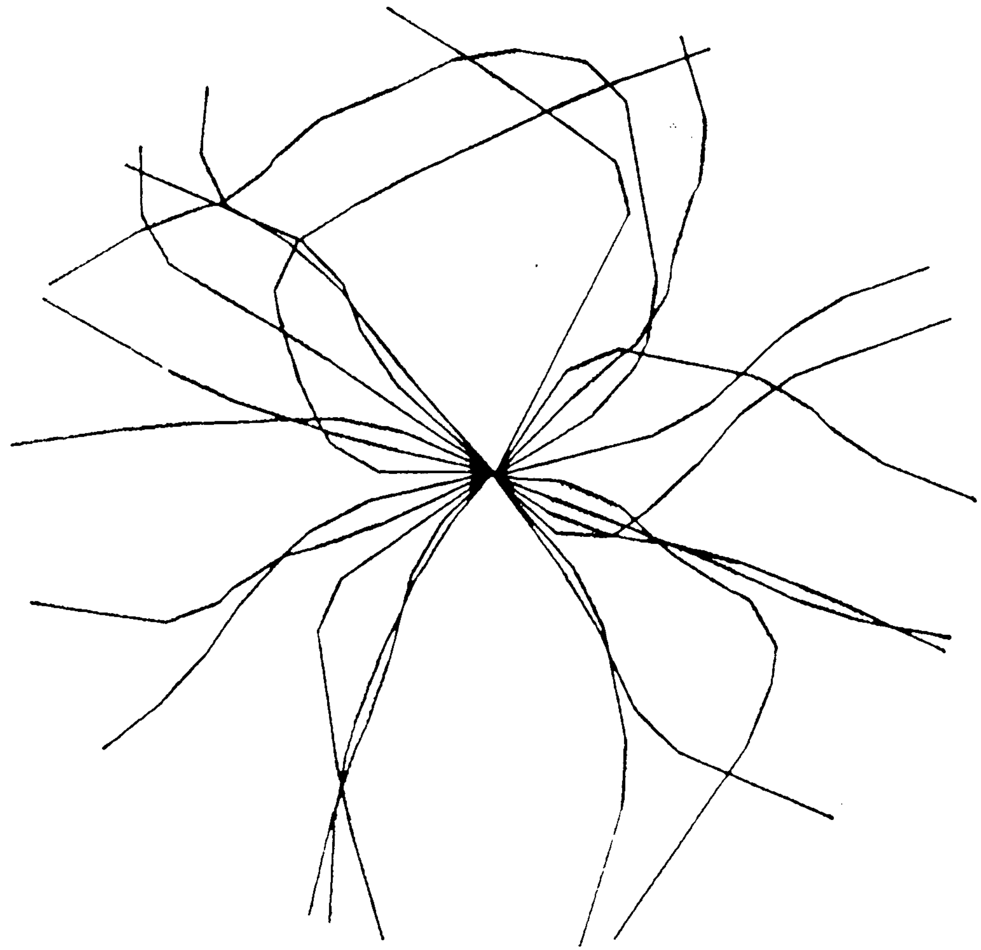
3D Monte Carlo calculations; radiation energy distribution in a propellant bed; LightTools, Optical Research Associates

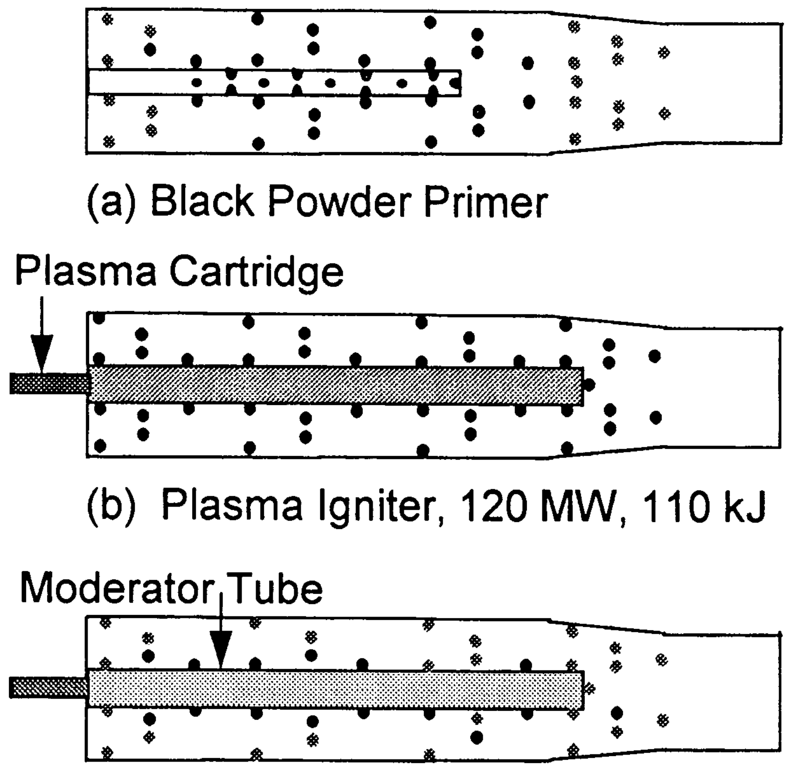




SOREQ 105-mm Simulator* Live Grain Location

ABERDEEN PROVING GROUND

WEAPONS & MATERIALS RESEARCH DIRECTORATE



(a) Black Powder Primer

(b) Plasma Igniter, 120 MW, 110 kJ

(c) Plasma Igniter, 70 MW, 65 kJ

- Unburned Propellant Grain
- Burned Propellant Grain

* L. Perelmutter, et al, "Experimental Study of Plasma Propagation and Ignition of Solid Propellant in a Gun Chamber", presented at the16th Intentional Ballistics Symposium September, 1996

105mm SPETC Gun Charge
NGEN Simulation

105mm cartridge with projectile "cap"

Inert polyacetal polymer grains: geometric and thermal properties approx. for M30 grains.

Centercore BP igniter: gas generation rate and distibution simulating radial holes & axial hole.

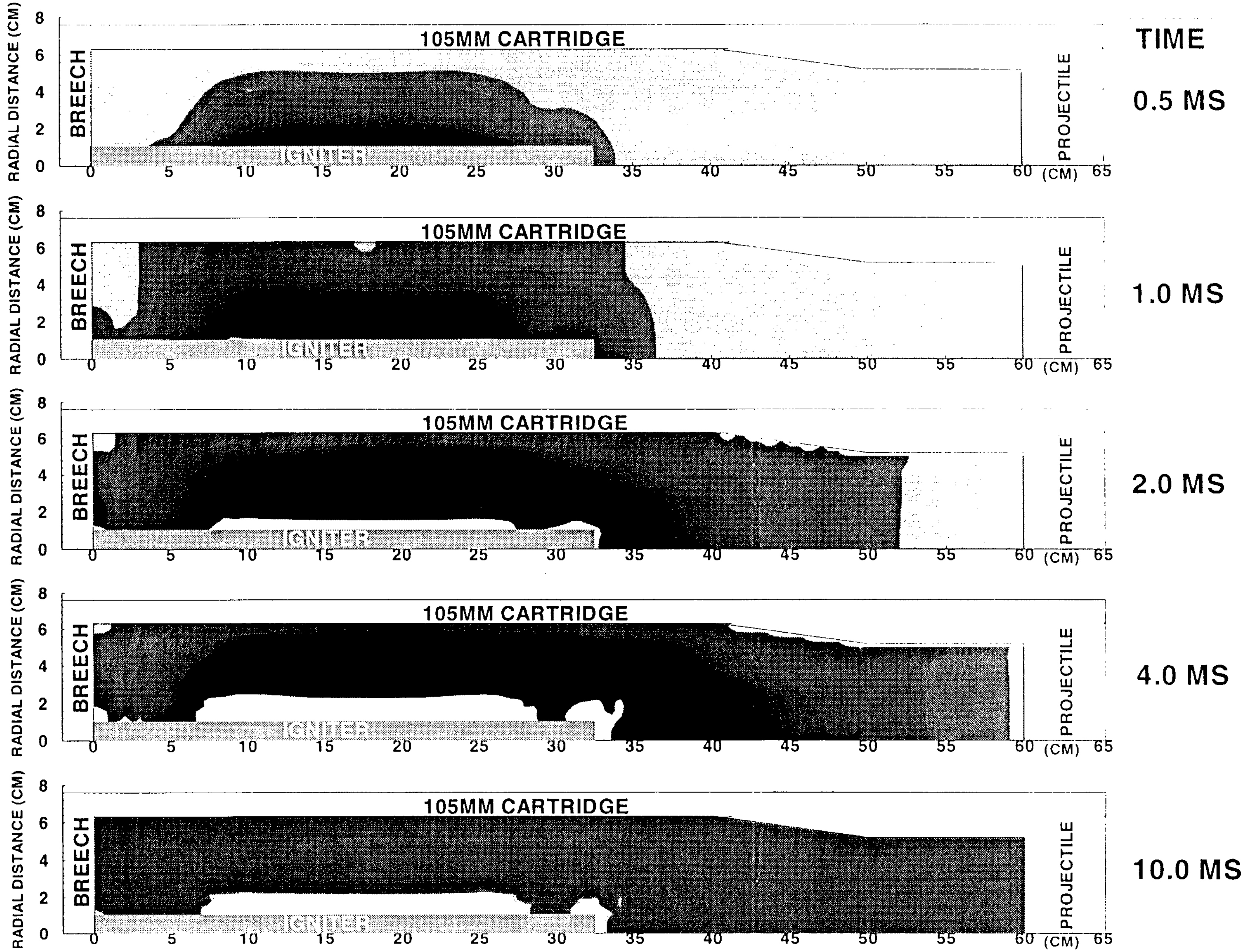
Plasma igniter: 70MW & 120MW peak powers, no tube bursting, no radiation, Powell's code used for plasma injection boundary conditions.

Centercore plasma igniter: same gas generation characteristics as BP igniter but gas has plasma properties (energy, density, mol. wgt.).

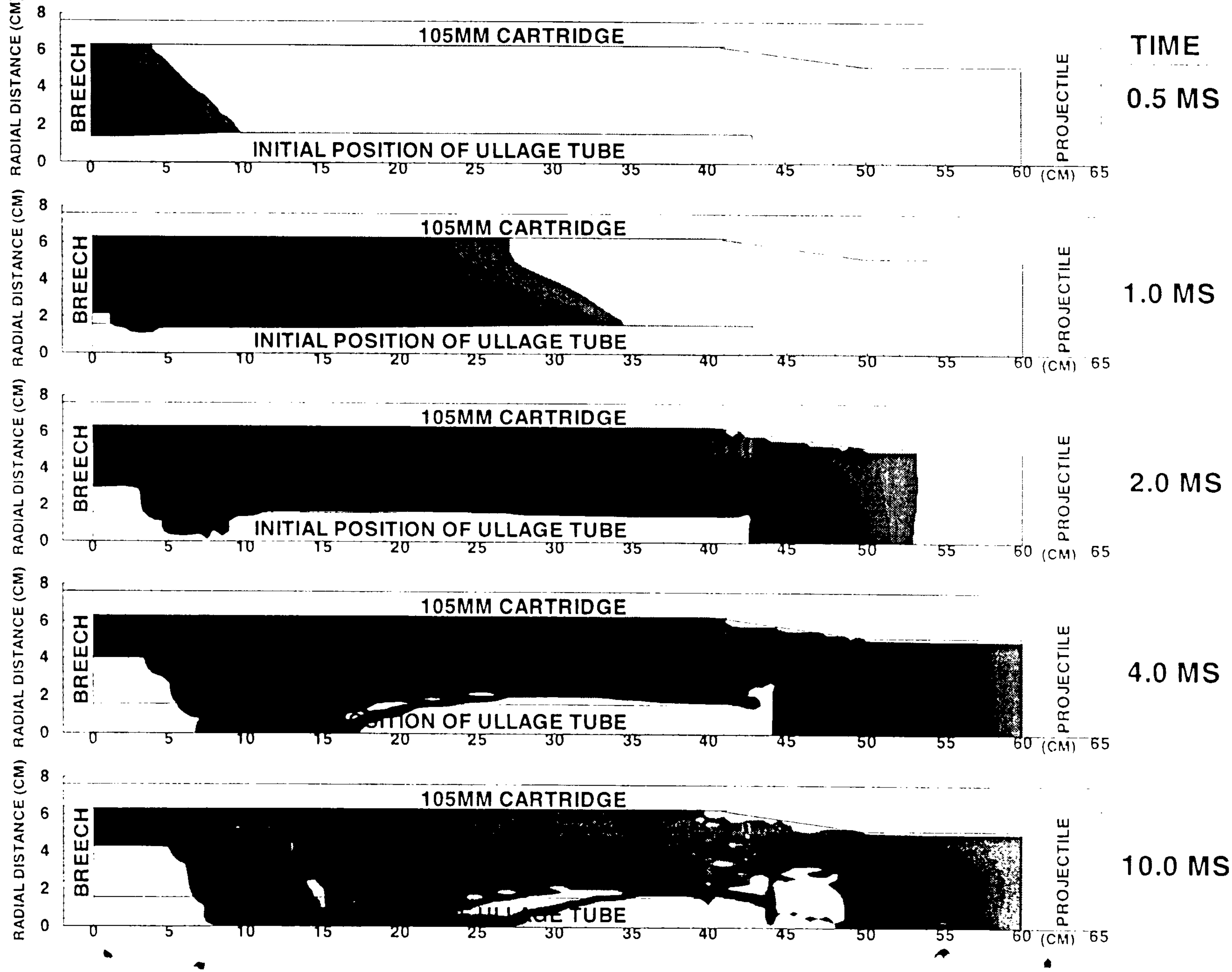
Plotting flamespread: $T > T_{ign}$ (M30)

(Nusca 10/97)

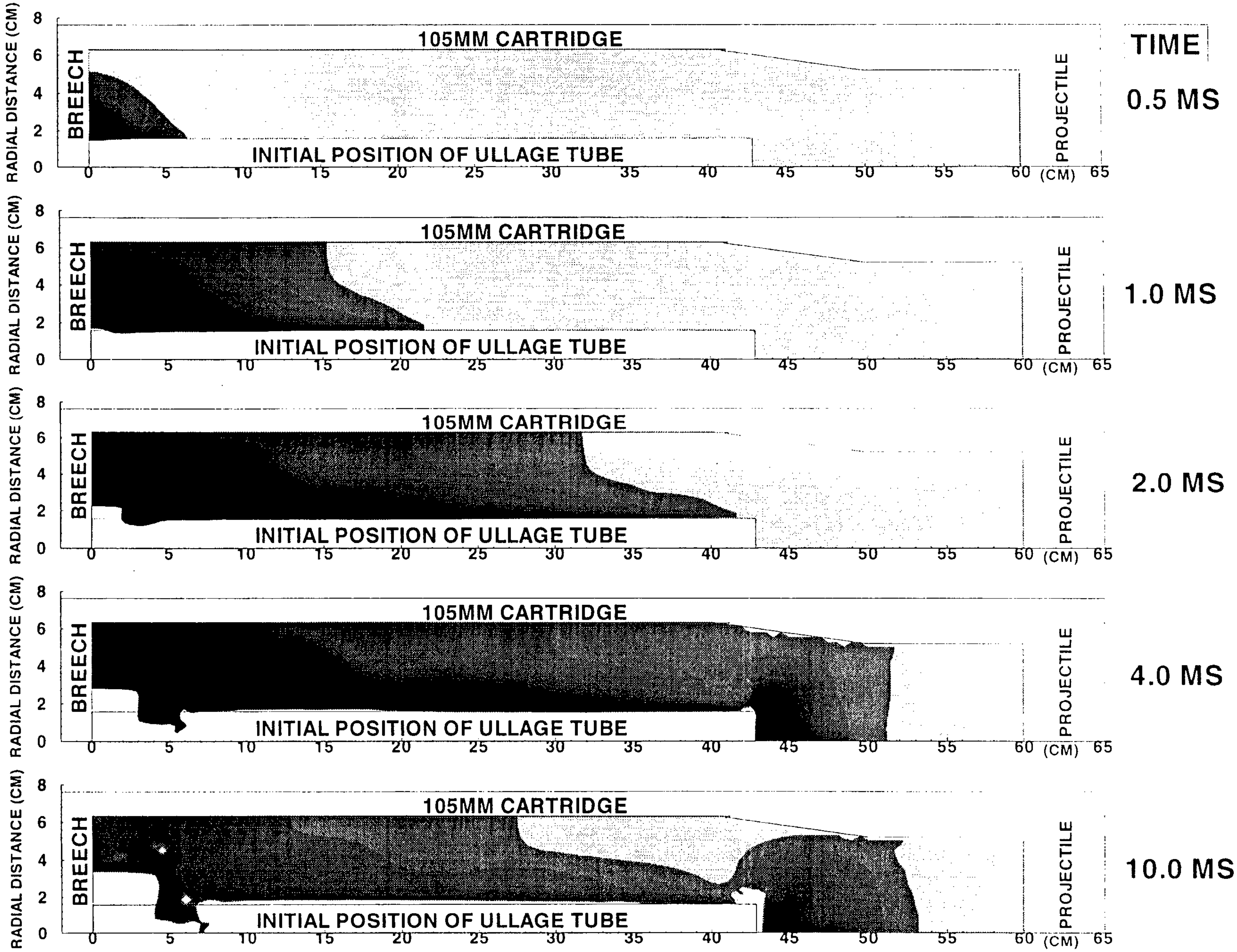
ARL-NGEN2 SIMULATION OF 105MM SOREQ TEST FIRING -- CONVENTIONAL IGNITER
SOLID PARTICLE TEMPERATURE CONTOURS (294K - 444K)



ARL-NGEN2 SIMULATION OF 105MM SOREQ TEST FIRING -- PLASMA IGNITER (120MW)
SOLID PARTICLE TEMPERATURE CONTOURS (294K - 444K)



ARL-NGEN2 SIMULATION OF 105MM SOREQ TEST FIRING -- PLASMA IGNITER (70MW)
SOLID PARTICLE TEMPERATURE CONTOURS (294K - 444K)



Conventional and Plasma Ignition

ABERDEEN PROVING GROUND

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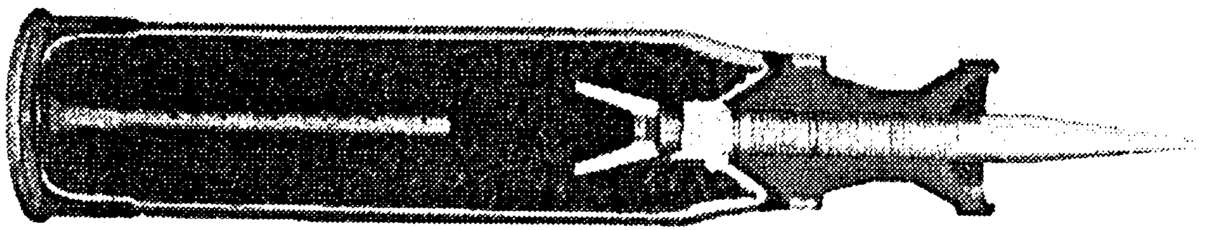
Ignition Delay

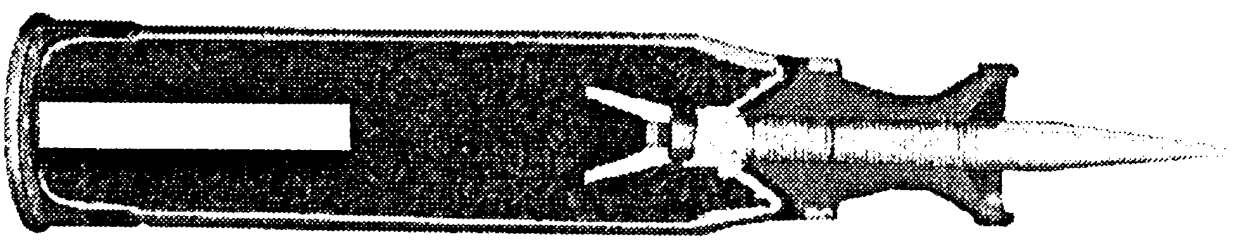
Conventional M865 Round with M125 Benite Primer*



24 ± 1 ms

*Approximate chemical energy of primer is 75 kJ

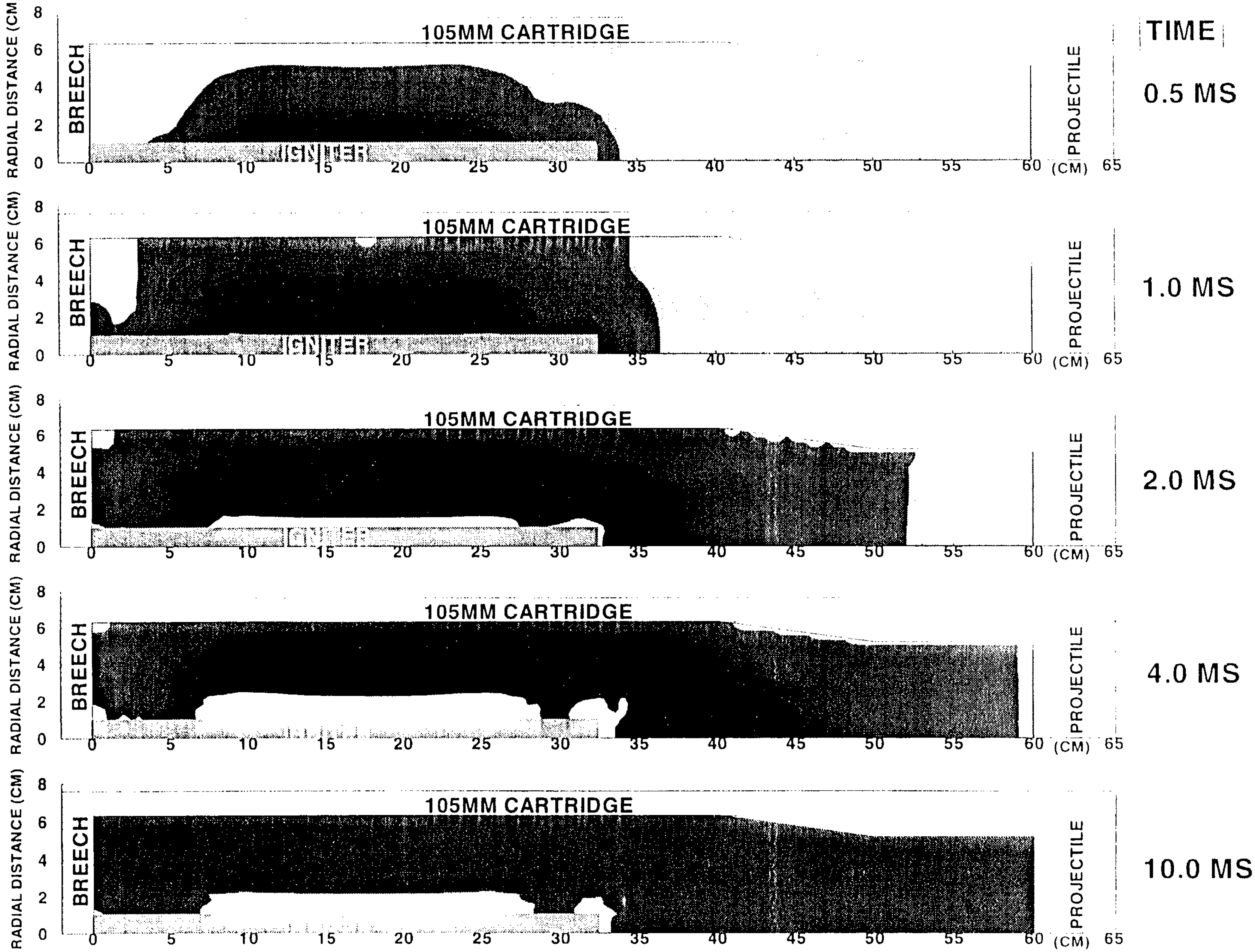
ETC M865 Round with Plasma Injector



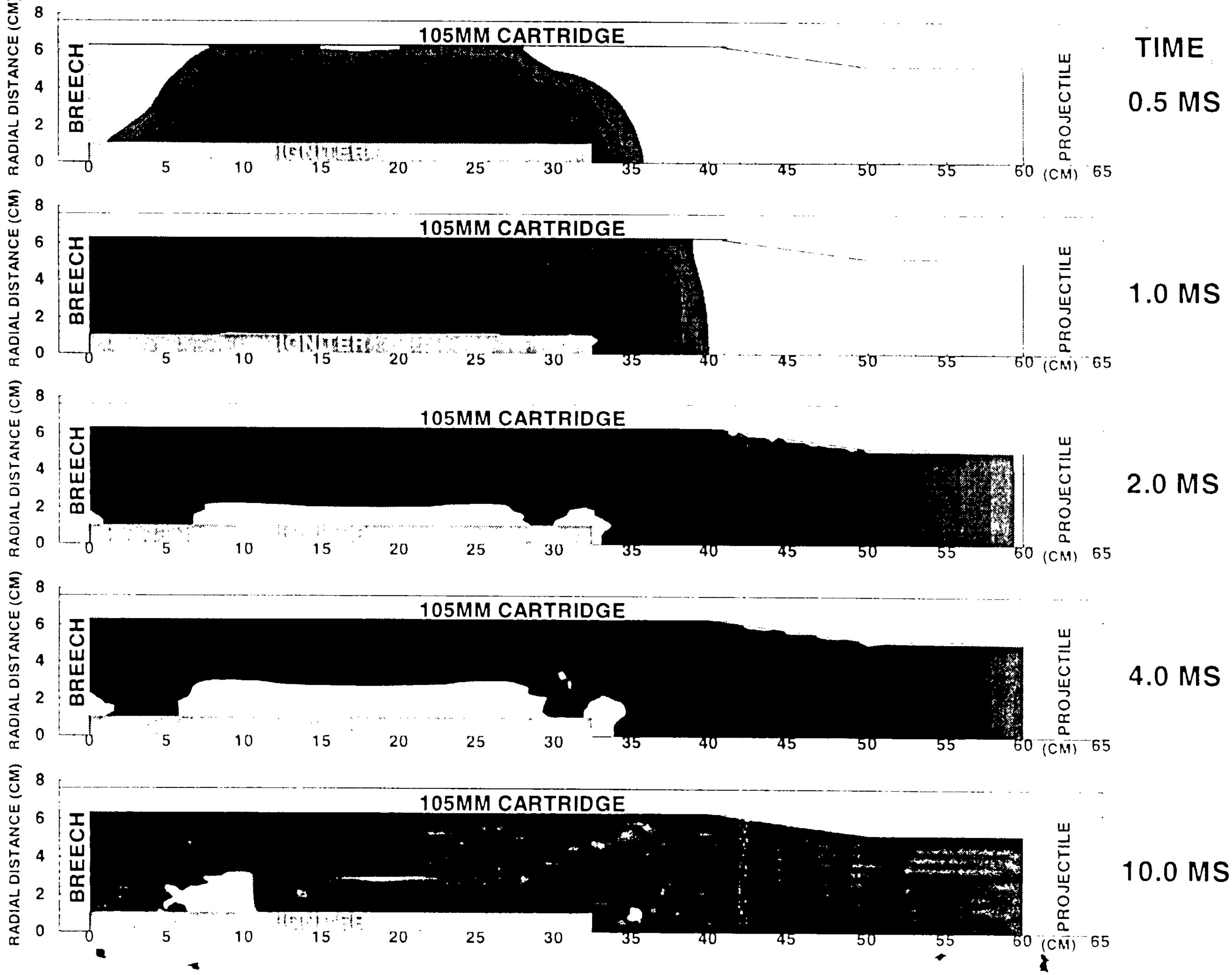
2.36 ± 0.04 ms

UDLP Gun Firings, Katulka & Dyvik, 33rd JANNAF Combustion Meeting November 1996

ARL-NGEN2 SIMULATION OF 105MM SOREQ TEST FIRING -- CONVENTIONAL IGNITER
SOLID PARTICLE TEMPERATURE CONTOURS (294K - 444K)



ARL-NGEN2 SIMULATION OF 105MM TEST FIRING -- "PLASMA-GAS" IGNITER SOLID PARTICLE TEMPERATURE CONTOURS (294K - 444K)



Plasma-Propellant Studies
Heat Flux Measurements

ABERDEEN PROVING GROUND

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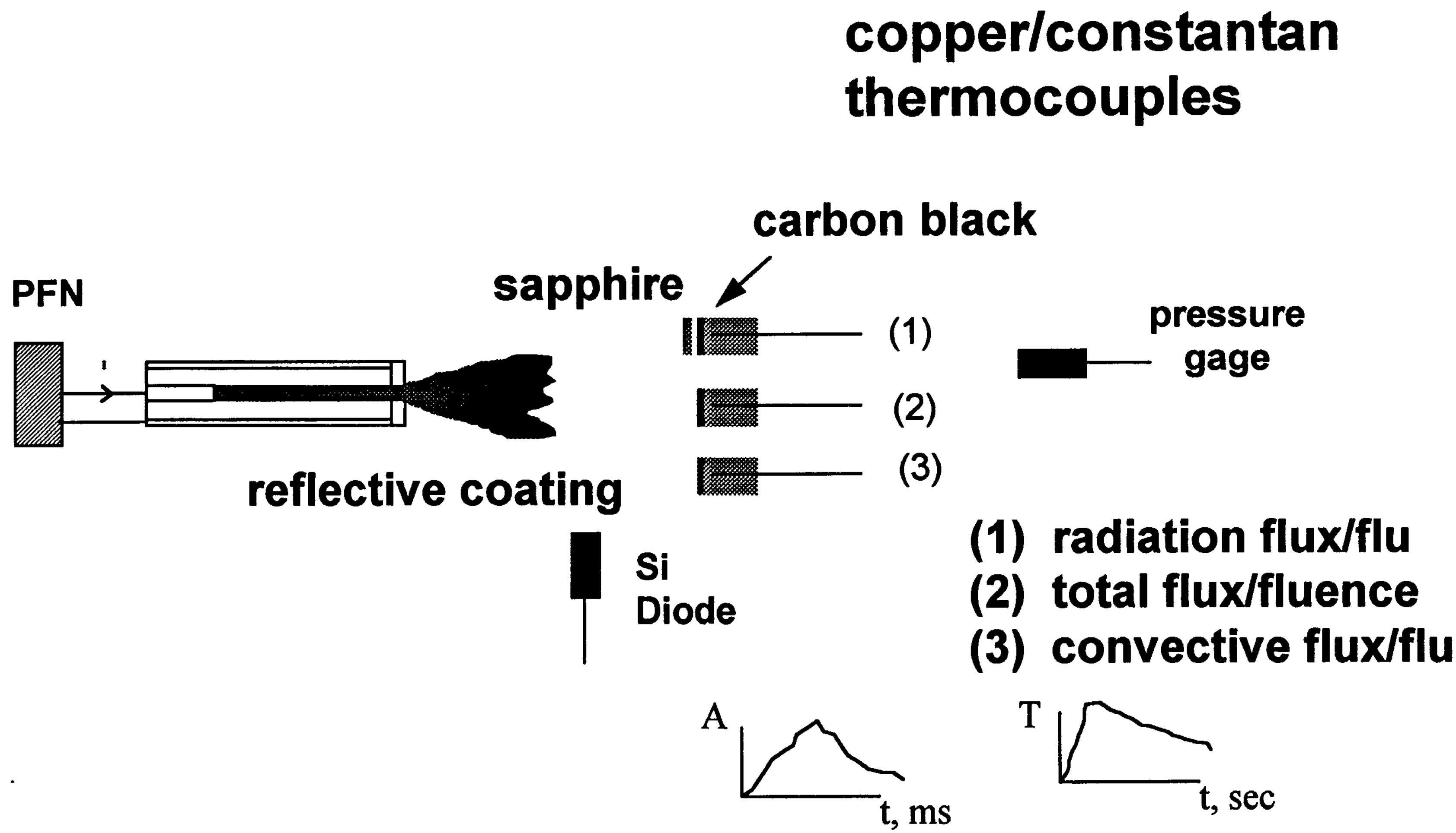

Conclusions

- True absorption coefficients determined
- Except for JA2 and M10, absorption in the visible is small; uv *may* be stronger
- NGEN; major contribution to ignition by plasma from convective heating
- Radiative heating calculations incomplete
- Heat flux gage to distinguish radiation and convection

Experiments

Modeling

ABERDEEN PROVING GROUND

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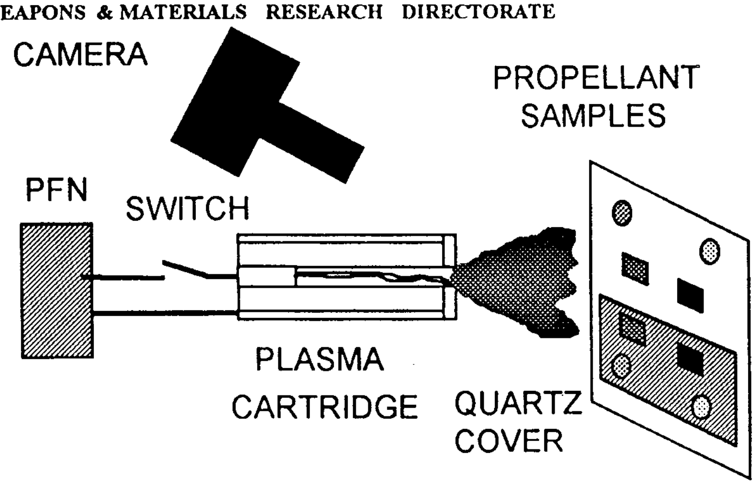


1. MECHANICAL EFFECTS, HIGH SPEED MICROPHOTOS

2. THERMAL EFFECTS, IR PHOTOS

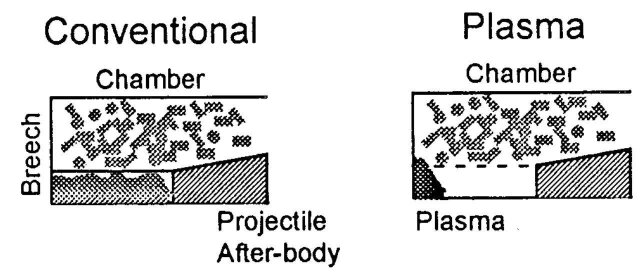
3. CHEMICAL REACTIONS, SURFACE RAMAN

4. CHEMICAL & PHYSICAL ANALYSIS OF PROPELLANTS

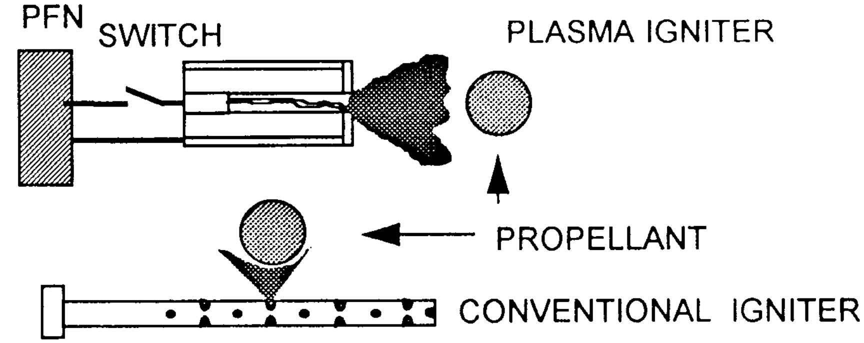
5. PROPELLANT OPTICAL PROPERTIES (INTEGRATING SPHERE)

6. PLASMA SPECTRAL CHARACTERISTICS

7. CONVECTIVE AND RADIATIVE PLASMA ENERGY DISTRIBUTION (PROPELLANT BED, FLUX GAGE)



1. CONVECTIVE (NGEN) AND RADIATIVE (LIGHTOOLS) PLASMA ENERGY DISTRIBUTION WITHIN A PROPELLANT BED



2. PLASMA EXPANSION AND INTERACTION WITH PROPELLANT (FAST3D)

3. CONVENTIONAL IGNITER INTERACTION WITH PROPELLANT (FAST3D)

4. MECHANICAL RESPONSE OF PROPELLANT TO PLASMA & CONVENTIONAL IGNITER

5. CHEMICAL MODELING OF PLASMA-PROPELLANT

Activities of Rheinmetall/TZN and Results of the R&D Programme Electrothermal-Chemical-Gun

Th. H.G.G. Weise, H.-K. Haak
TZN Forschungs- und Entwicklungszentrum
Unterlüß GmbH

Table of Contents

- Introduction
- Basic Considerations on the interior ballistic Processes of the ETC Technologies
- ETC Working Group and Programme Schedule
- Basic Investigations 45ml Closed Vessel
- Basic Investigations 500ml Closed Vessel
- Basic Investigations 6.5l Firing Simulator
- Investigations 105mm ETC Demonstrator
- Summary and Conclusions

Introduction

ETC Technologies have the goal to increase the performance of a barrel gun by the interaction of electrothermally absorbed energy with the combustion of a modified solid propellant charge.

Main factors of influence are:

- ETC ignition und combustion control of charges with increased loading density
- ETC propelling gas conversion with Hydrogen additives

The investigations have been started within the German R&D Programme 120/140/ETC in January 1996. A first technical milestone is defined in November 1997 by proving first ETC principles in a model calibre firing demonstrator.

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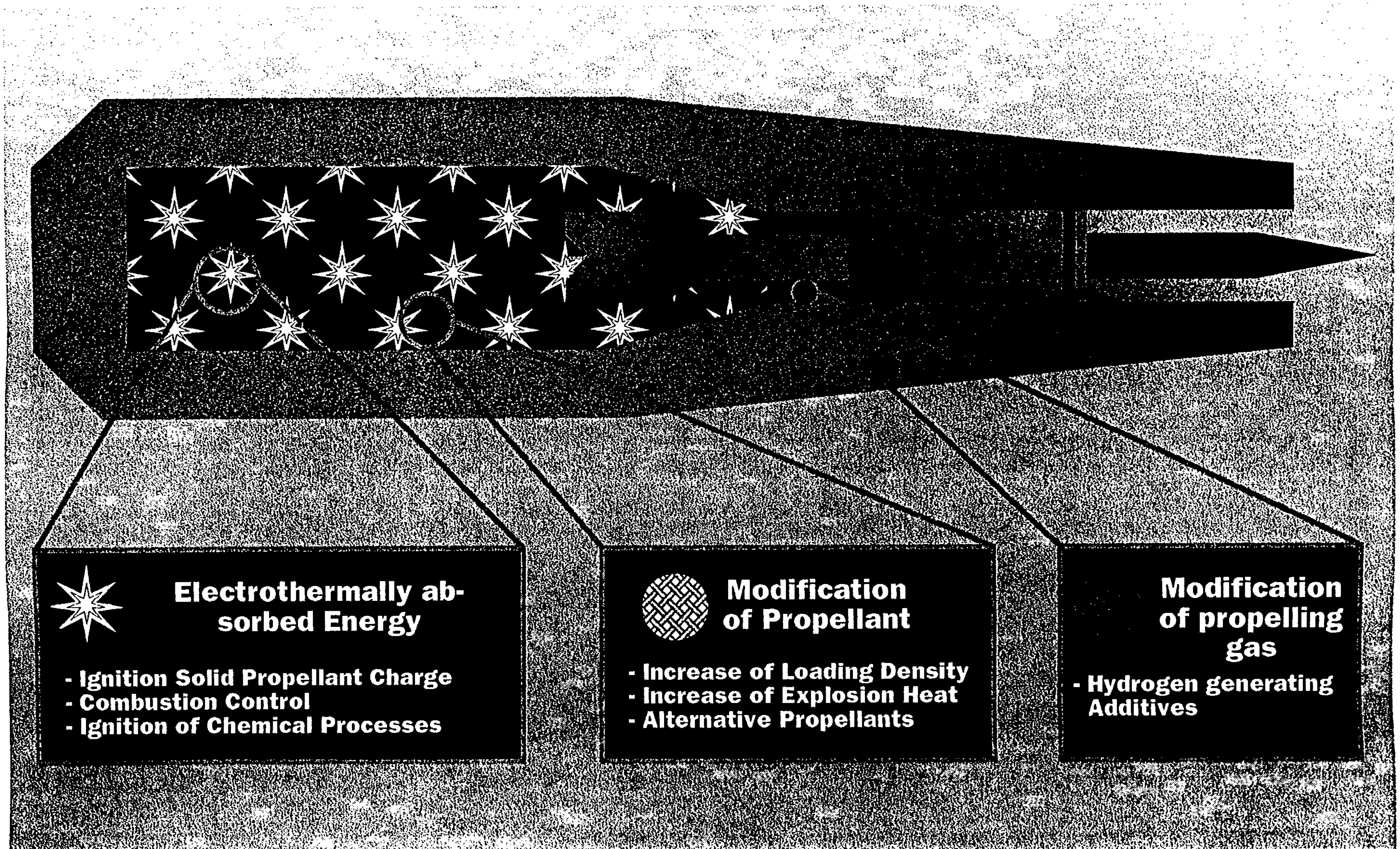
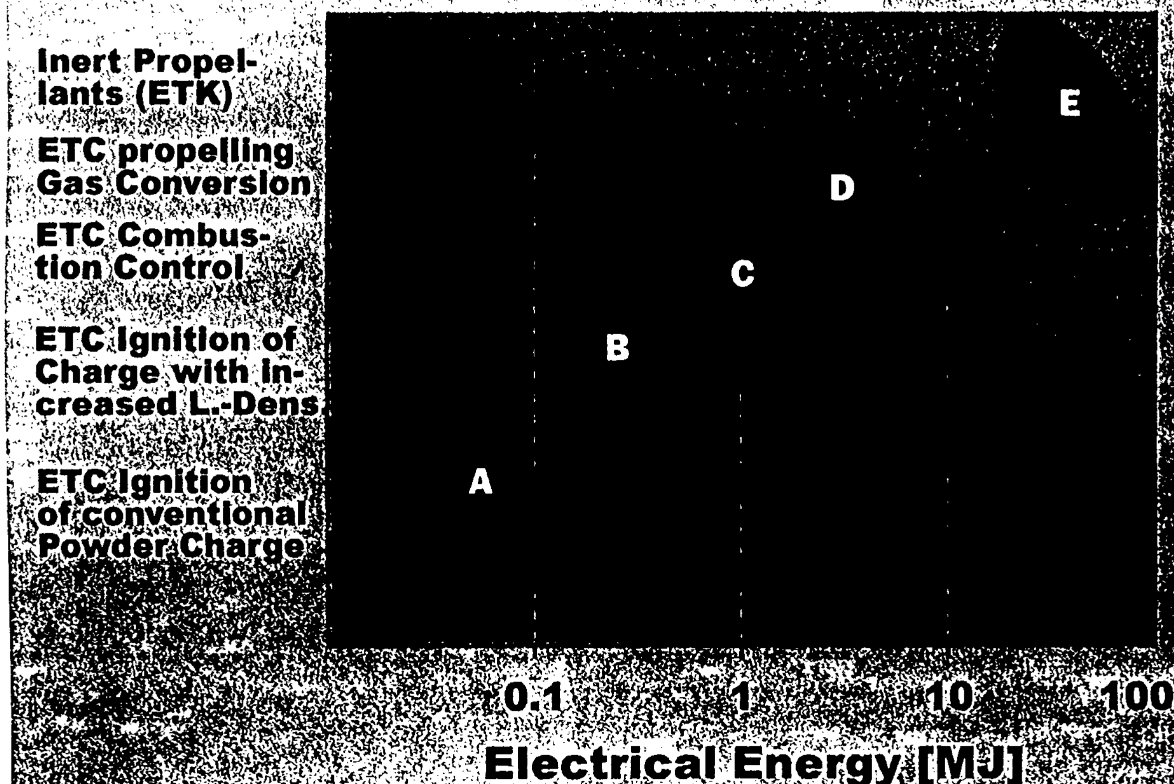
Basic Considerations Interior Ballistic Processes



Basic Considerations Interior Ballistic Processes

Classification of ETC Technologies

Powder Charge Modifications and Electrical Energy Consumption



Interior Ballistic Results

Type	Measure	Wo	Vo
A	electrical Ignition		
B	electrical con-trolled Ignition	++	+
C	electrical con-trolled combus-tion	++	+
D	electrical ini-tiated H2-Addi-tion	++	++
E	electrical eva-poration of in-ert propellants	++	+++

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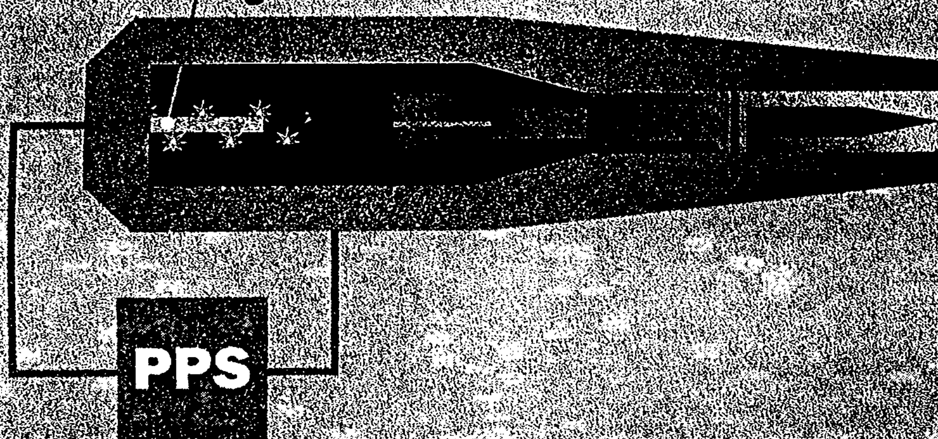
Basic Considerations Interior Ballistic Processes

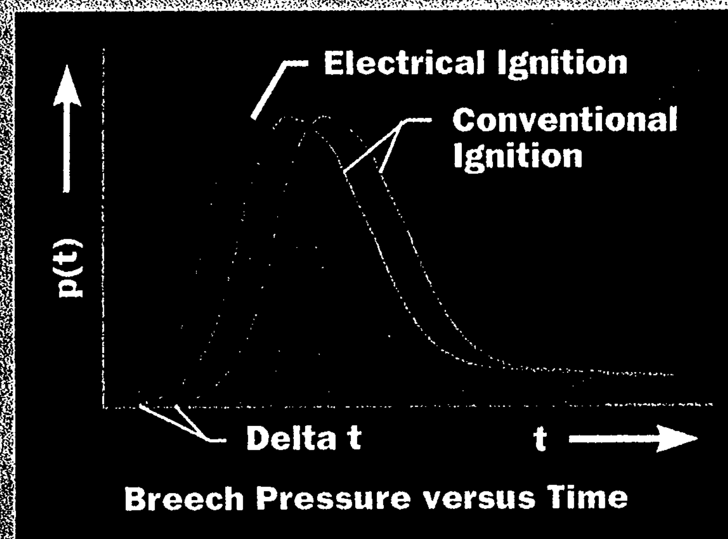
Type A:
Electrical Ignition of conventional Powder Charges

Modification



Modification of Igniter
PPS: <100 kJ

Interior Ballistic Result



Decrease of Ignition Jitter

Precision Improvement

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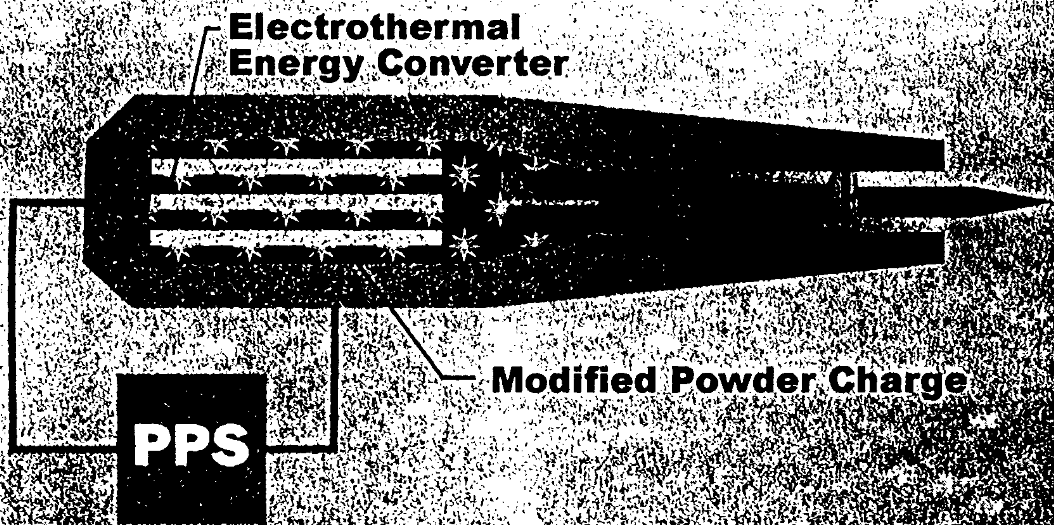
Basic Considerations Interior Ballistic Processes

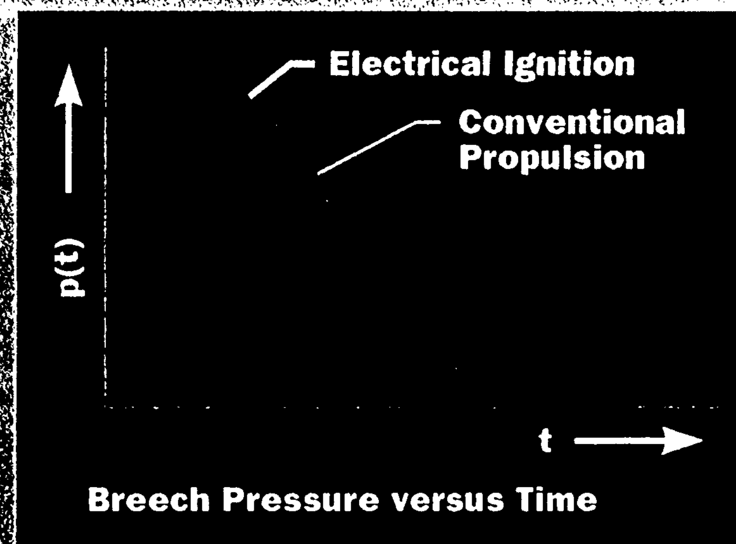
Type B:
Electrical controlled Ignition of Powder Charges with increased Loading Density

Modification



Modification of Powder Charge
Absorption of electrothermal Energy
PPS: 300 kJ until 600 kJ

Interior Ballistic Results



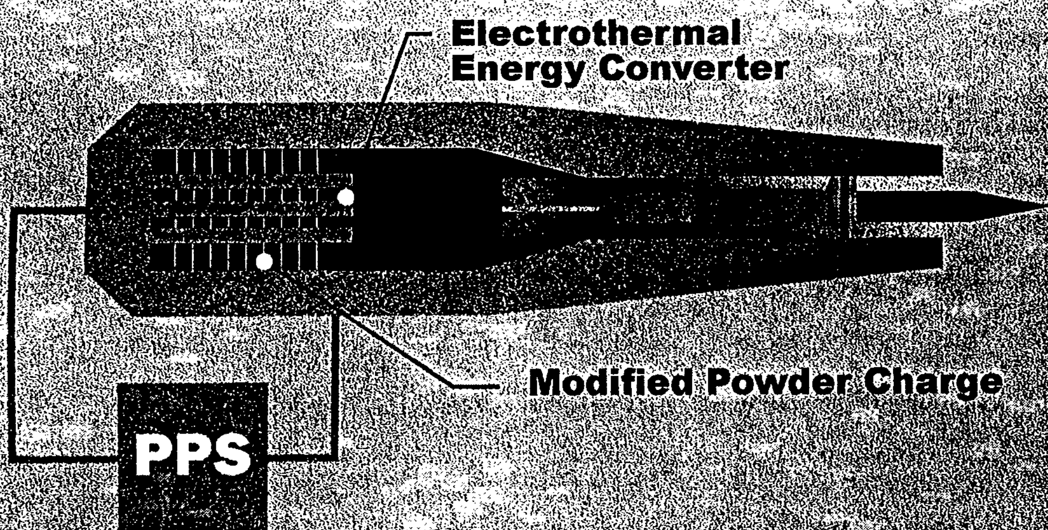
Increase of Propulsion Energy

Increase of Muzzle Energy

Basic Considerations Interior Ballistic Processes

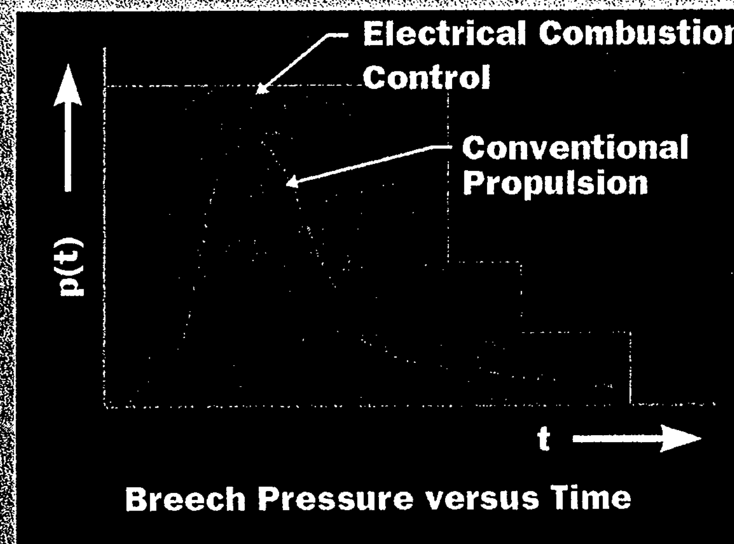
Type C: Electrical controlled Combustion of Powder Charges with increased Loading Densities

Modification



Modification of the Powder Charge
Absorption of electrothermal Energy
PPS: 0.9 MJ bis 1.8 MJ

Interior Ballistic Results



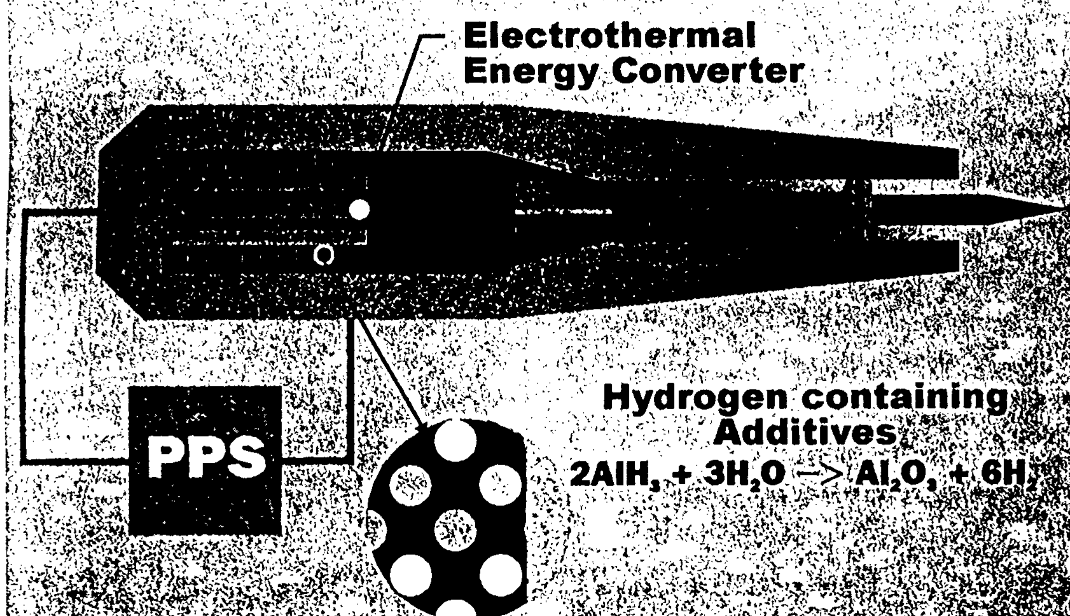
Increase of Propulsion Energy
Decrease of Temperature Coef-ficient

Increase of Muzzle Energy

Basic Considerations Interior Ballistic Processes

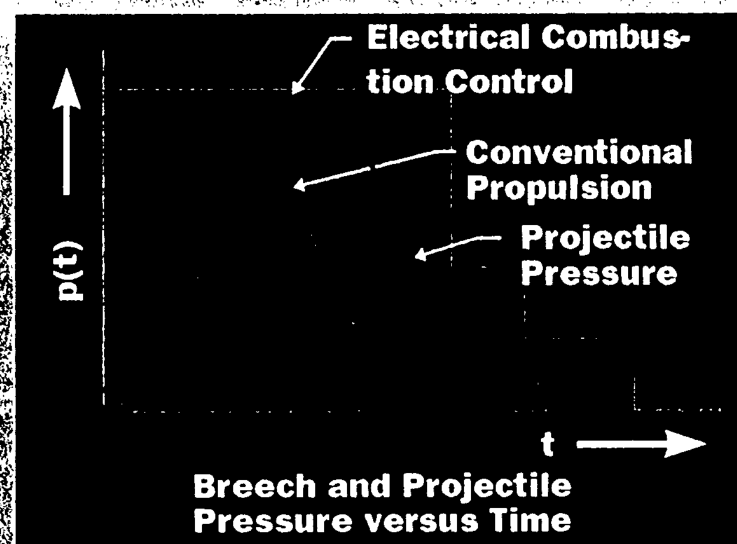
Type D:
Electrical controlled Combustion of Powder Charges with increased Loading Densities and integrated Additives

Modification



Modification of Powder Charge
Absorption of electrothermal Energy
PPS: 2.5 until 5 MJ

Interior Ballistic Results



Increase of Propulsion Energy, Decrease of Temperature Coefficient, Conversion of propelling Gas

↓ ↓ ↓

Increase of Muzzle Energy and Muzzle Velocity

German R&D Programme ETC Gun

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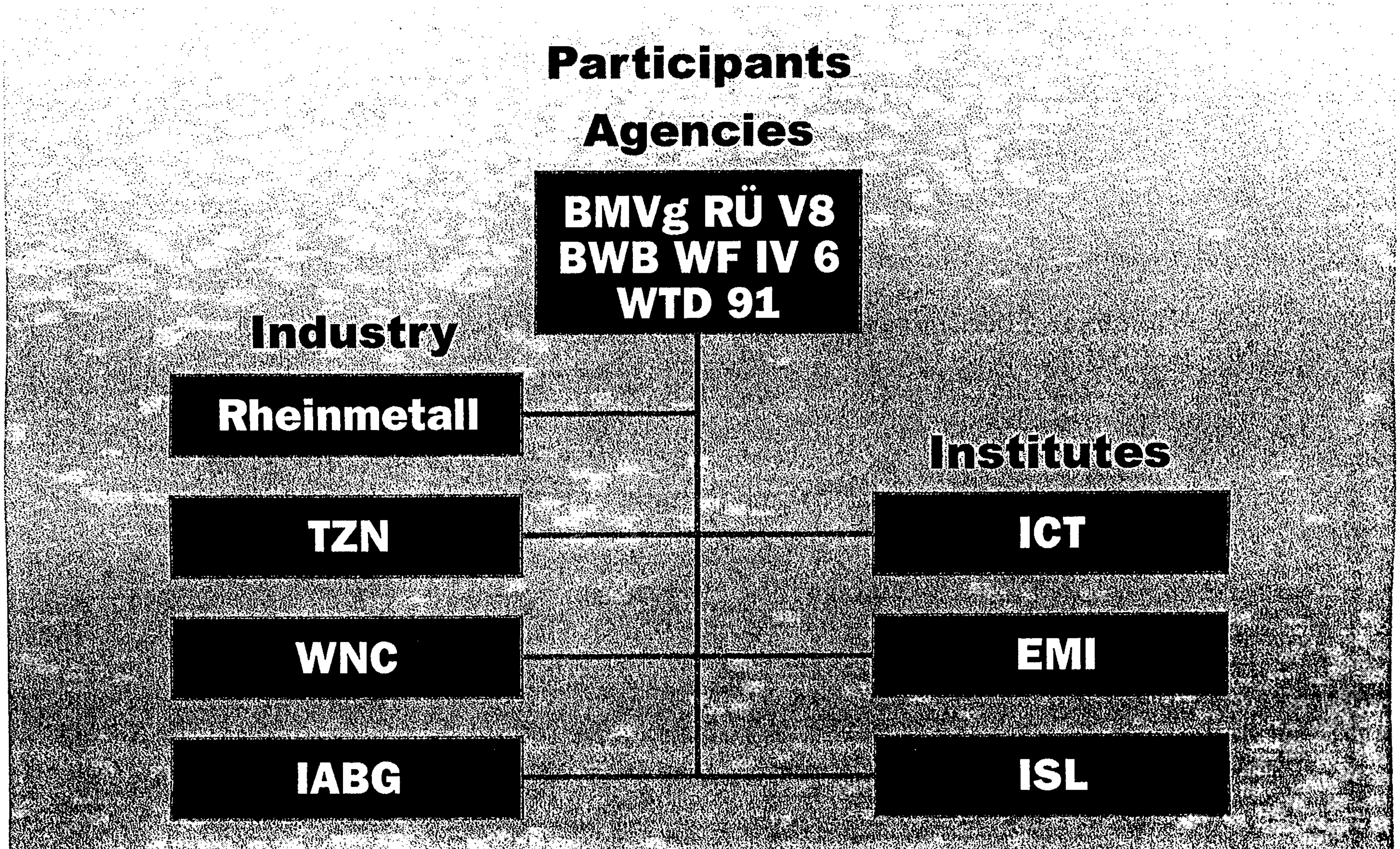
ETC Programme Structure



ETCENG11.cdr / Dr. Weise / 24.11.97

- Vermerk: vertraulich -

ETC Programme Schedule

Working Topics and Milestone Goals

Phase I: 1996 until 1997

Basic Investigations on ETC Ignition and Combustion Control

Basic Investigations on ETC Hydrogen Generation

Basic Investigations on ETC Control of Hydrogen Generation with Powder Combustion

↓

Proof of ETC Principles in Model Calibre Firings

ETC Programme Schedule

Working Topics and Milestone Goals

Phase II: 1998 until 1999

Continuation of Investigations with 6.5l Firing Simulator and with 105mm ETC Demonstrator for Performance Improvement

Design of 120mm Technology Demonstrator

Fabrication and Start Up of 120mm Demonstrator

Experimental Investigations 120mm and Proof of Performance

Demonstration of at least 20% Performance Improvement in Comparison with LKEII L55 120mm Serial Gun

Basic Investigations 45ml Closed Vessel

Goals

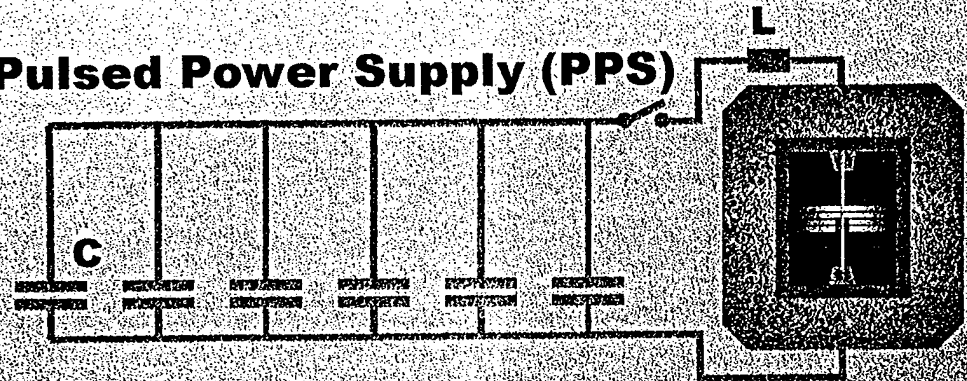
Investigation of Interactions of Arc Discharges with solid Propellant (JA2 type) with different geometrical Forms at

- **different loading denssities**
- **different electrical energy levels**
- **different pulse durations**

Basic Investigations 45ml Closed Vessel

Experimental Setup

Pulsed Power Supply (PPS)



Data PPS:

Capacitance C	104, 208,..., 416µF
Inductance L	70µH, 10mH
Charge Voltage	5 kV ... 25 kV
Modules	1

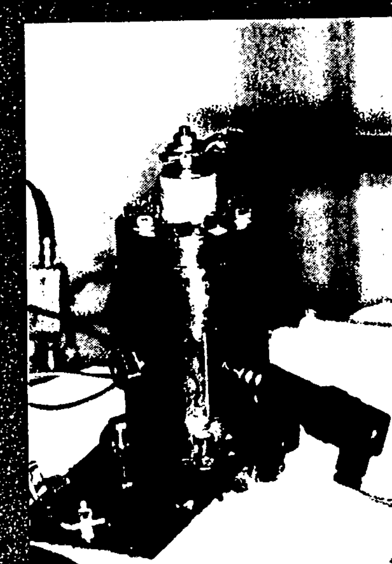
Data Closed Vessel:

Electrode Distance	70mm
Chamber Diameter	24mm
max. operating Pressure	350MPa
Chamber Volume	45ccm

Charge Setup:

JA2 Grains	13.2g, 62kJ
JA2 Discs	9.6g, 45kJ

Photografic View
45ml Closed Vessel



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Basic Investigations 45ml Closed Vessel

Technical Status in November 1997

Work performed:

Sept. 96: - Setup of experimental Hardware
- Start up of experimental Hardware

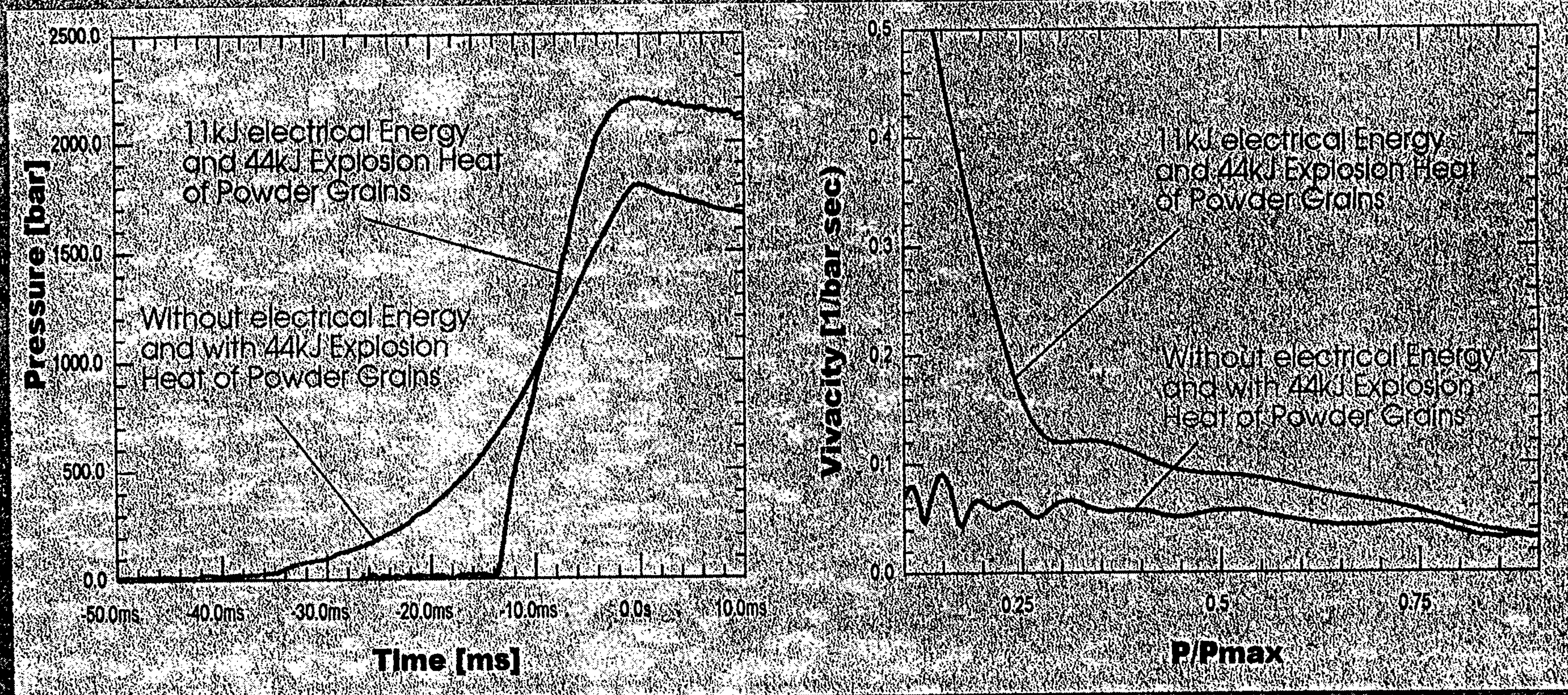
October 96: - Investigations on ETC Combustion Control with JA2 Grains

Nov. 96: - Investigations on ETC Combustion Control with JA2 Discs

Further Procedure 97:
The Investigations are finished

Basic Investigations 45ml Closed Vessel

Characteristic experimental Results on ETC Ignition effects



Basic Investigations 45ml Closed Vessel

Summary of Results

Ignition of JA2 Grains with electrothermally absorbed Energy possible

Ignition of JA2 Discs with electrothermally absorbed Energy possible

Powder Conversion with electrothermally absorbed Energy adjustable by

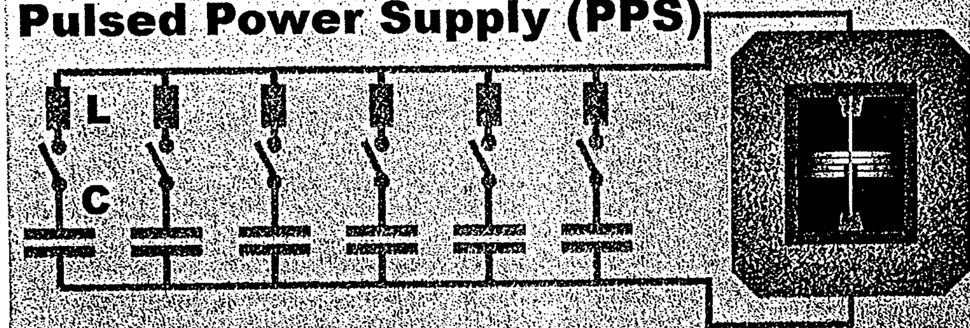
- Amount of electrical Energy
- electrical Pulseshape

Conversion Velocity of compact Powder Discs by electrical Energy adjustable to Requirements of Acceleration

Basic Investigations 500ml Closed Vessel

Experimental Setup

Pulsed Power Supply (PPS)



Data PPS:

Capacitance C	52, 104, 156, 206µF
Inductance L	20, 80, ..., 705, 1240µH
Charge Voltage	10 kV ... 33 kV
Modules	6

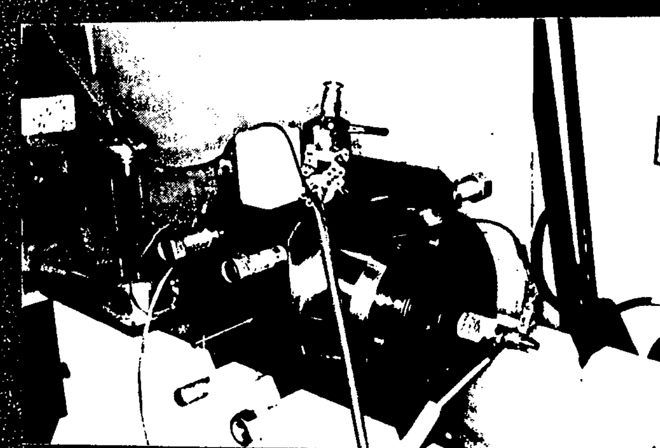
Data Closed Vessel:

Electrode Distance	100mm
Chamber Diameter	70mm
max. operating Pressure	300MPa
Chamber Volume	500ccm

Charge Setups:

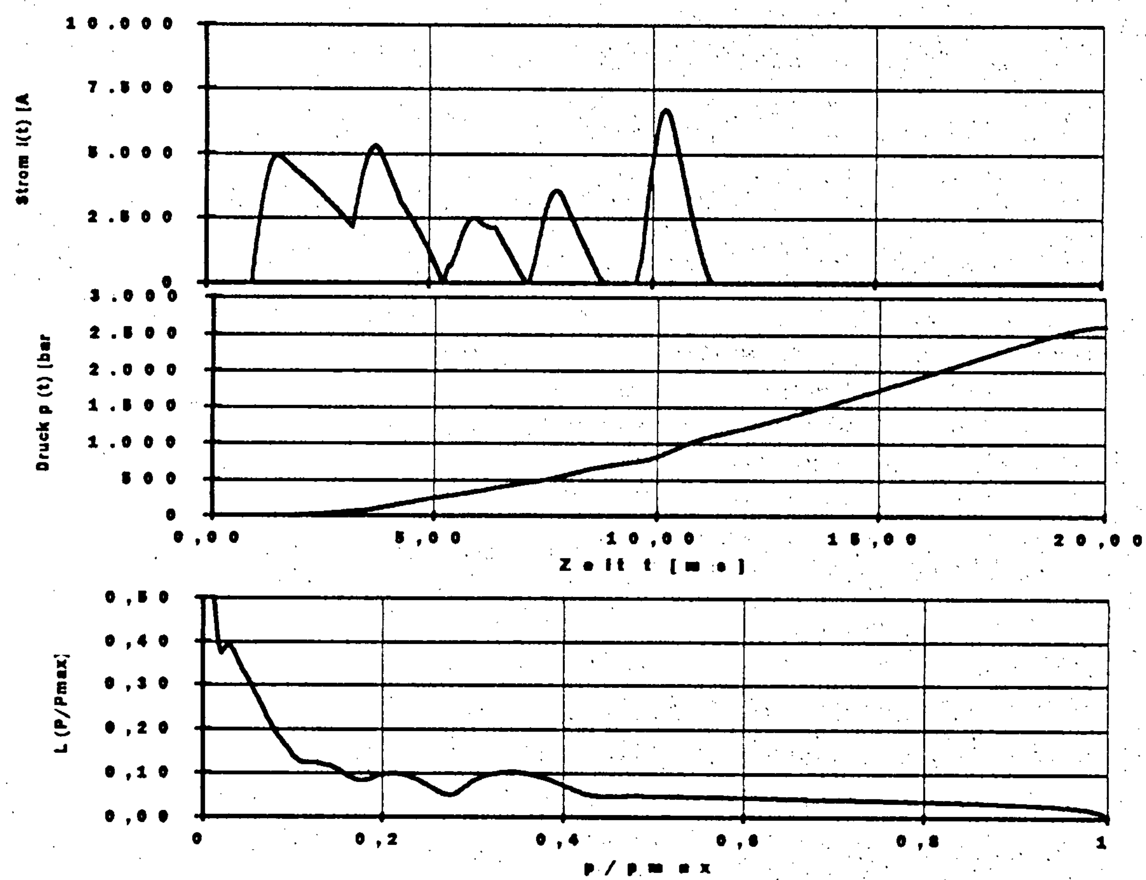
JA2 Grains	112g, 448kJ
JA2 Discs	112g, 448kJ
$ALH_3 + H_2O$	50g+50g 670kJ

Photografic View 500ml Closed Vessel



Basic Investigations 500ml Closed Vessel

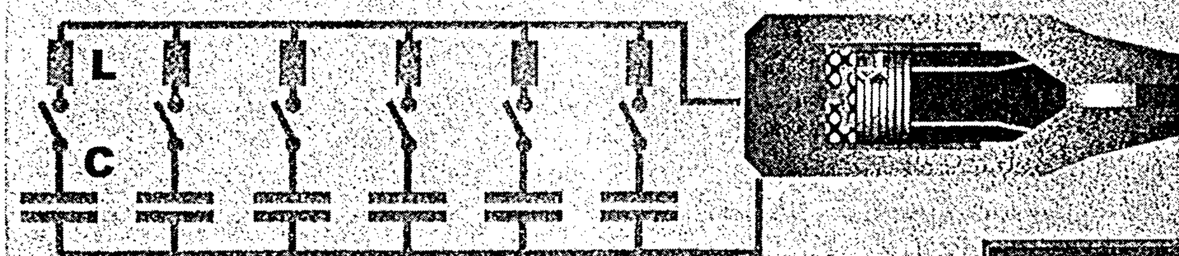
Characteristic experimental Results



Basic Investigations 6.5l Firing Simulator

Experimental Setup

Pulsed Power Supply (PPS) **Simulator**



Charge Setups:

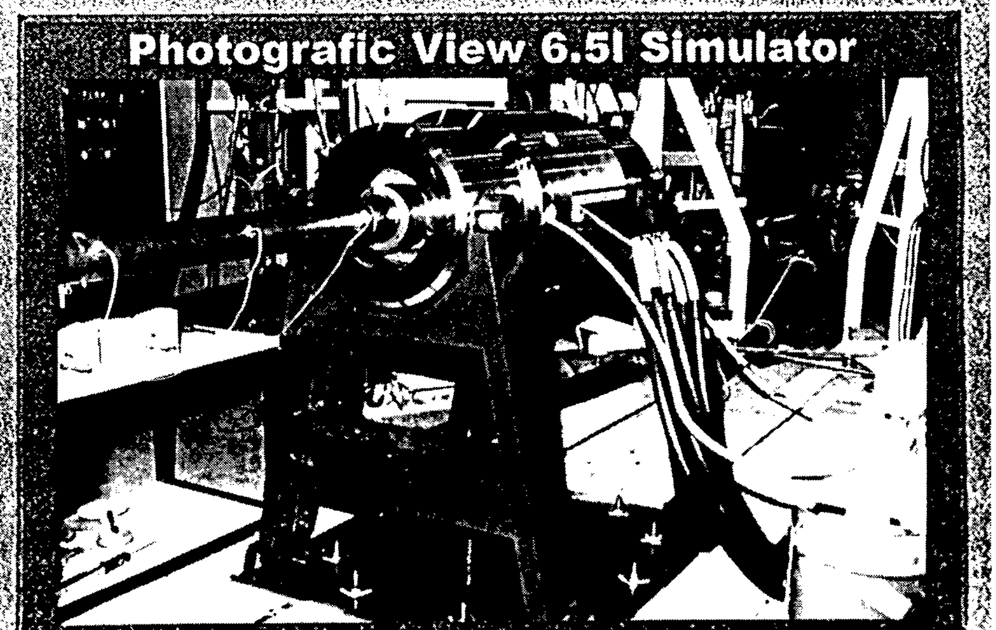
JA2 Discs	1.5kg, 7.2MJ
$ALH_3 + H_2O$	190g+190g 2.4MJ

Data PPS:

Capacitance C	52, 104, 156, 206µF
Inductance L	20, 80, ..., 705, 1240µH
Charge Voltage	10 kV ... 33 kV
Modules	6

Data Firing Simulator:

Barrel Diameter	50mm
Barrel Length	4.5m
max. operating Pressure	400MPa
Chamber Volume	6,500ccm
Mass of Piston	2 .. 4kg



Basic Investigations 6.5l Firing Simulator

Technical Status in November 1997

Work performed:

August 97:
- Start of Modification of experimental Platform
- Start of Modification of ETG-Plasmaburners to ETC Mode
- Start of Fabrication of JA2 Discs

September:
- Integration of Simulator in TZN Pulsed Power Laboratory
- Setup and Calibration of Diagnostics

October:
- Start up of Simulator with inert Charge Setups

November
- Performance of first Investigations with JA2 Discs

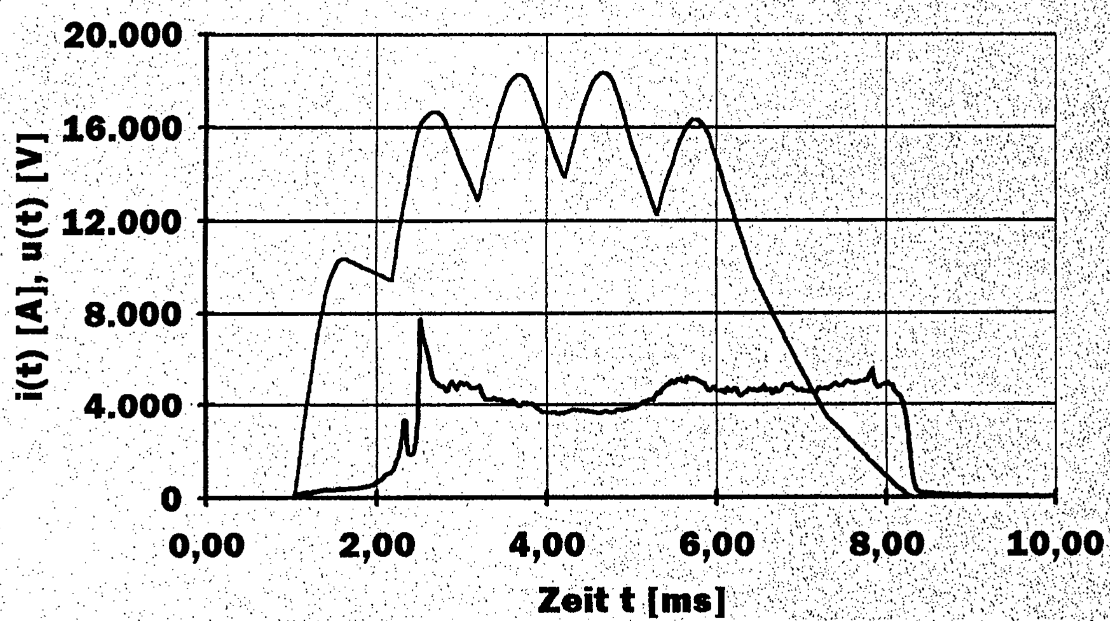
Further Procedure 97:

December:
- Continuation of Investigations with JA2 Disc for Preoptimization of experimental Parameters for 105mm ETC Demonstrator Experiments

Basic Investigations 6.5l Firing Simulator

Characteristic experimental Results

Discharge Current and Arcvoltage versus Time



Experimental Parameters

PPS:

Capacitance	5x208µF
Inductance	5x705µH
Charge Voltage	22kV
Charge Energy	250kJ
Trigger Delay	5x1ms

Firing Simulator:

Charge Setup	7 PE Discs
Arc Channels	3x15mm

Basic Investigations 6.5l Firing Simulator

Summary of Results

Experiments with inert PE Discs and few Powder Discs with 15mm Arcchannel Diameter indicate on instable Arc Characteristic

Decrease of Arcchannel Diameter indicate parallel Burning of Arcs

ETC Effect of Conversion of Powder Discs at low Loading Densities is not sufficient up to now

Investigations 105mm ETC Demonstrator

Technical Status in November 1997

Work performed:

May 97:
- Decision to perform ETC Model Calibre Firings with 105mm Electric Gun Demonstrator FEUERSTELLUNG 2000

August
- Start of Modification of experimental Platform
- Start of Modification of ETG Plasmaburners for ETC
- Preparation of 30MJ PPS System for ETC
- Start of Fabrication of 3.2kg Projectiles
- Interior Ballistic Simulations for Definition of Charge

October:
- Performance Tests with 30MJ PPS System in ETC Mode
- Calibration of Diagnostics
- Integration of 105mm ETC Demonstrator
- First Firing Tests with conventional Charge Setup and ETC Ignition and Powder Conversion Control

Further Procedure 97:

November:
- Continuation of 105mm ETC Firing Tests and Proof of ETC Principle
- Milestone Presentation on November 26th and 27th

TZN
Forschungs- und Entwicklungszentrum Unterlüß GmbH

Investigations 105mm ETC Demonstrator

Experimental Schedule in 1997

Shot No.	Charge Setup	Electr. Energy	Pulseshape	Projectile	Date
GETC-01a	4kg JA2, 2kg inert	500kJ	single	3.2kg Cylinder	29.10.97
GETC-02a	5kg JA2, 1kg inert	500kJ	single	3.2kg Cylinder	30.10.97
GETC-03a	6kg JA2	500kJ	single	3.2kg Cylinder	31.10.97
GETC-03b	6kg JA2	500kJ	single	3.2kg Cylinder	04.11.97
GETC-04a	6kg JA2	750kJ	single	3.2kg Cylinder	04.11.97
GETC-04b	6kg JA2	750kJ	single	3.2kg Cylinder	05.11.97
GETC-05a	6kg JA2	2*250kJ	double	3.2kg Cylinder	05.11.97
GETC-05b	6kg JA2	2*250kJ	double	3.2kg Cylinder	06.11.97
GETC-05c	6kg JA2	2*250kJ	double	3.2kg Cy. + Fins	07.11.97
GETC-03c	6kg JA2	500kJ	single	3.2kg Cy. + Fins	11.11.97
GETC-06a	6kg JA2	2*375kJ	double	3.2kg Cy. + Fins	12.11.97

Investigations 105mm ETC Demonstrator

Experimental Schedule in 1997

Shot No.	Charge Setup	Electr. Energy	Pulseshape	Projectile	Date
GETC-06b	6kg JA2	2*375kJ	double	3.2kg Cy. + Fins	13.11.97
GETC-07a	6kg JA2	500kJ	single	3.2kg Penetrator	14.11.97
GETC-07b	6kg JA2	2*250kJ	double	3.2kg Penetrator	25.11.97
GETC-04d	6kg JA2	750kJ	single	3.2kg Penetrator	26.11.97
GETC-06c	6kg JA2	2*375kJ	double	3.2kg Penetrator	27.11.97
GETC-08a	5kg JA2, 1kg JA2 D.	2*375kJ	double	3.2kg Cylinder	27.11.97
GETC-08b	5kg JA2, 1kg JA2 D.	2*375kJ	double	3.2kg Cylinder	28.11.97
GETC-09a	-	-	-	-	-
GETC-09b	-	-	-	-	-
GETC-10a	-	-	-	-	-
GETC-10b	-	-	-	-	-

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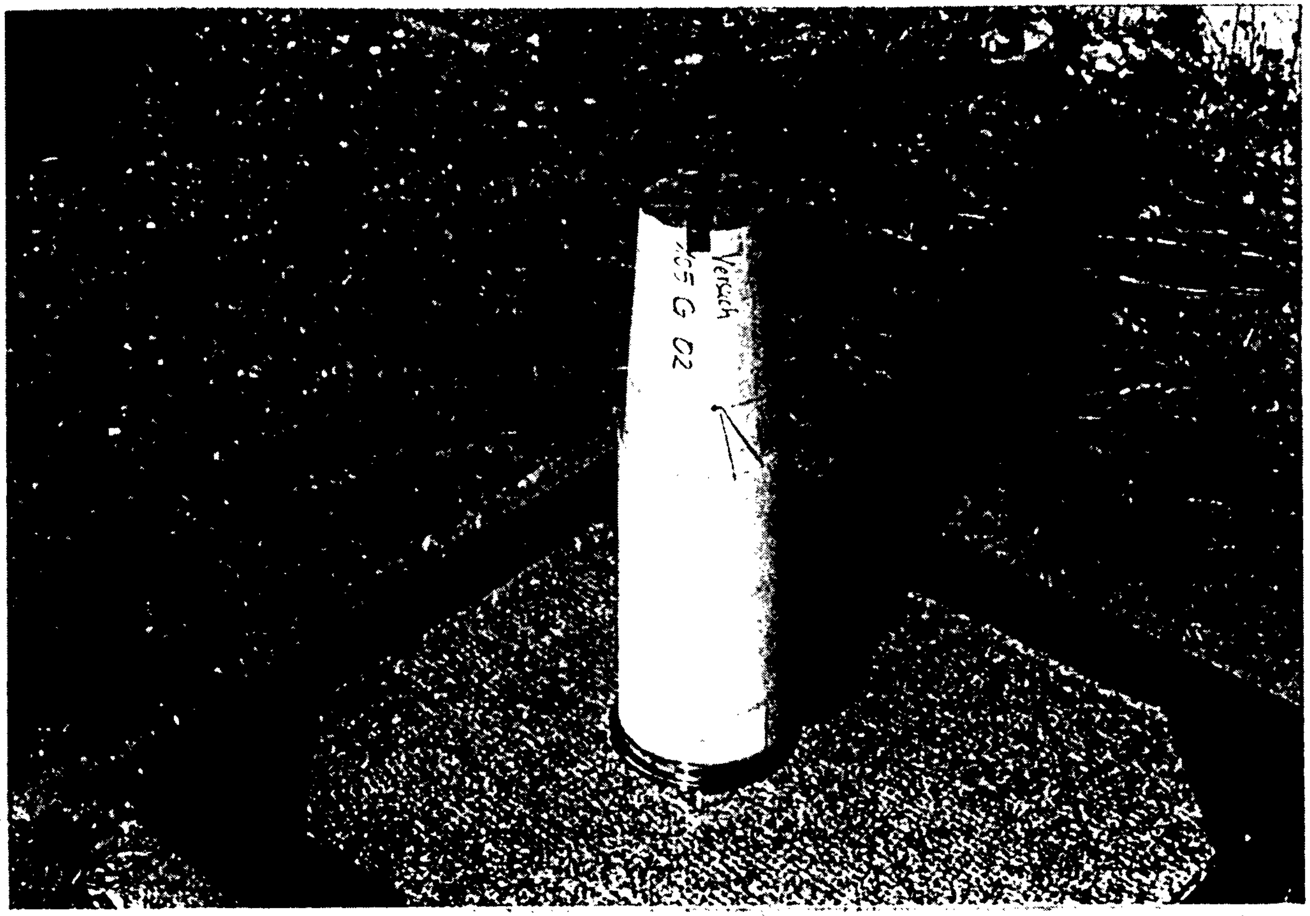
Unterlüß Gmt

Investigations 105mm ETC Demonstrator



German R&D Programme ETC Gun

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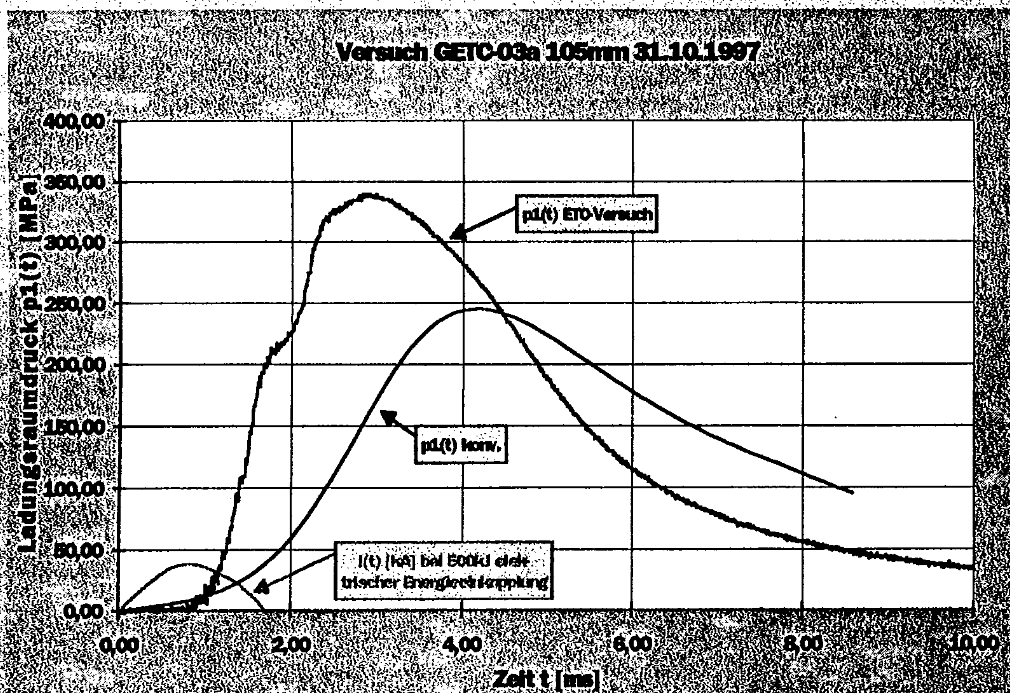
Unterlüß GmbH

Investigations 105mm ETC Demonstrator

Characteristic experimental Results



Experimental Setup

Calibre:	105 mm
Projectile:	3.2 kg
Barrel:	6 m

Paramters

Electrical

Capacitance:	2.6 mF
Inductance:	130 µH
Charge Voltage:	20 kV
Charge Energy:	500 kJ

Charge

Type:	JA2
Mass:	6 kg
Qex:	28.2 MJ

Firing Results

Muzzle Velocity	1,872m/s
Muzzle Energy	5.61 MJ
Efficiency	19.5%

Deutsches F&T-Programm ETC-Kanone

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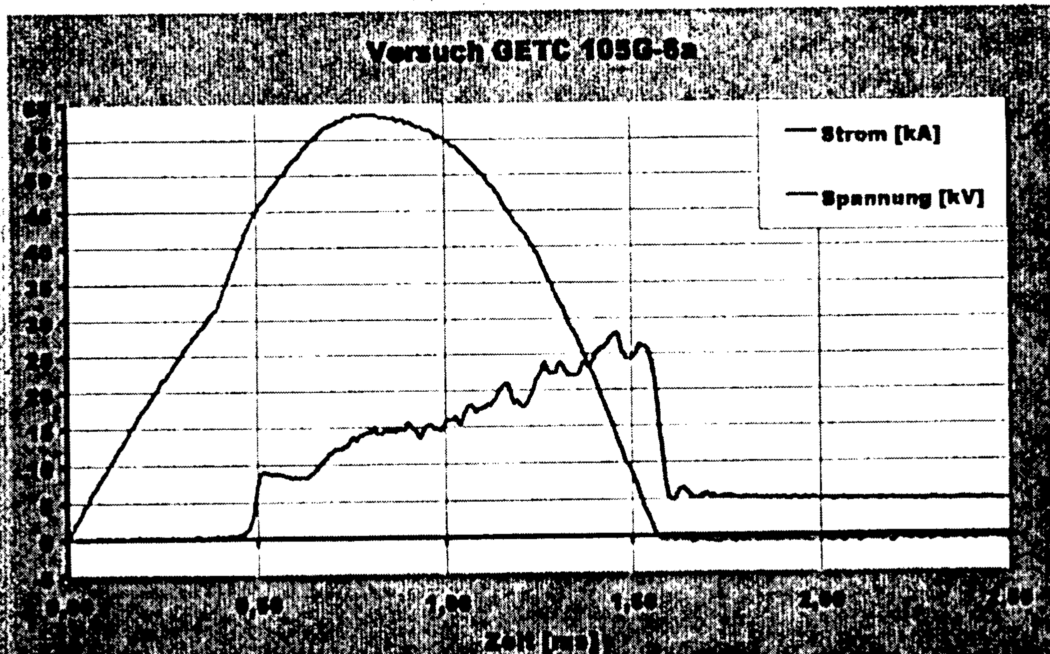
Forschungs- und Entwicklungszentrum Unterlüß GmbH

Untersuchungen 105-mm-ETC-Demonstrator

Charakteristisches Beschußergebnis



Versuchsergebnisse

	ETC
Münd.-Geschw.	1.908 m/s
Münd.-Energie	5,79 MJ
Wirkungsgrad	20 %

Versuchsaufbau

Kaliber: 105 mm
Geschoß: 3,2 kg
Rohr: 6 m

Versuchsparameter Elektrisch

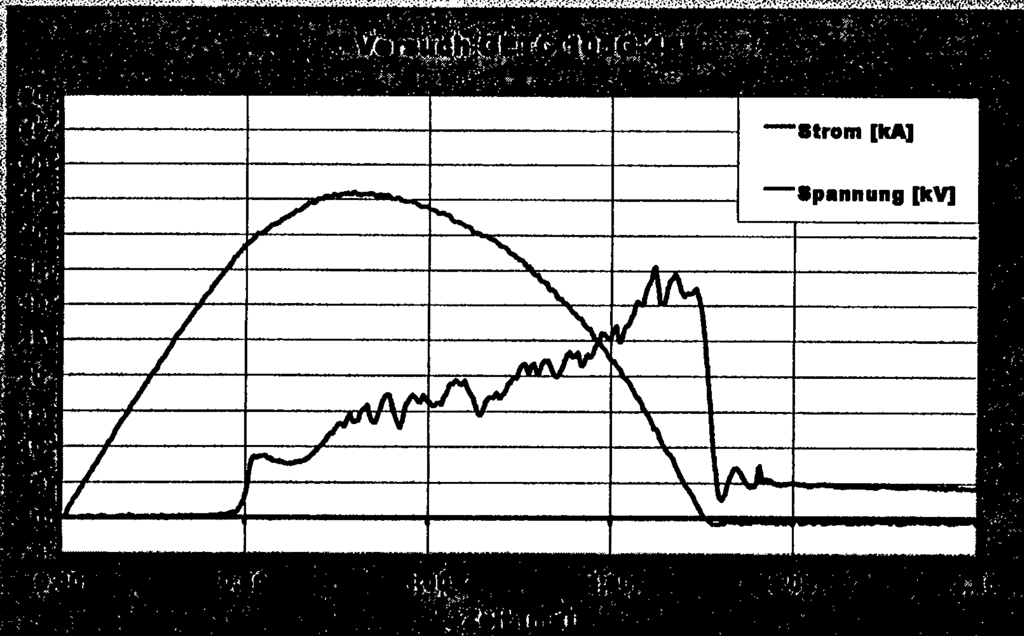
Kapazität: 1.38 mF
Induktivität: 260 µH
Ladespannung: 25 kV
Ladeenergie: 859 kJ
Zündverzugszeit: 400 µs

Treibladung

TLP-Typ: JA2
Masse TLP: 6 kg
Masse Inert: 0 kg
Qex: 28,2 MJ

Untersuchungen 105-mm-ETC-Demonstrator

Charakteristisches Beschußergebnis



Versuchsaufbau

Kaliber: 105 mm
Geschoß: 3,2 kg
Rohr: 6 m

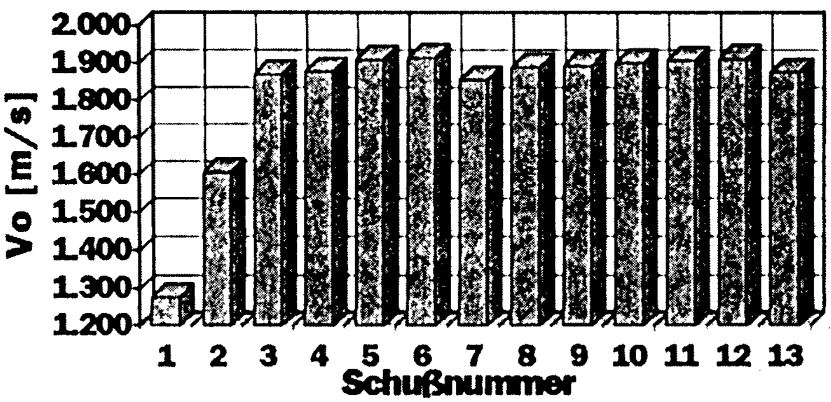
Versuchsparameter

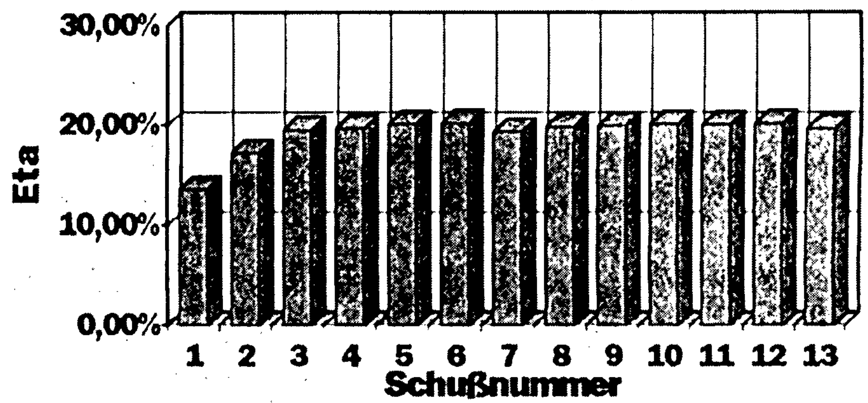
Elektrisch

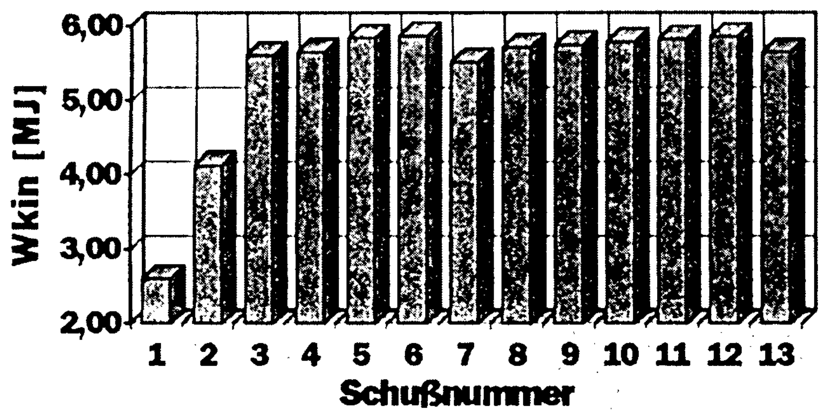
	ETC
Münd.-Geschw.	1.915 m/s
Münd.-Energie	5,71 MJ
Wirkungsgrad	20 %

Investigations 105mm ETC Demonstrator

Firing Results







Conclusions

Results of Closed Vessel Investigations on ETC Conversion transferrable to Firings

Powder Ignition and Conversion with ETC adjustable by

- **electrical Energy Level**
- **electrical Pulseshape**

No ETC Interaction on Stiffness of Projectile Fins

Investigations 105mm ETC Demonstrator

Evaluation of present Results

Influence of electrothermally absorbed Energy on the Conversion of solid Propellant is perceptible clearly both in Closed Vessel and in Firings

Chemical Conversion of Mixtures of Metal Hydrids with Water by electrothermally absorbed Energy is proved in Closed Vessel Experiments

Conversion of Mixtures of Metal Hydrids with Water and with Powder is adjustable by electrothermally absorbed Energy (Proved in Closed Vessel Experiments)

High Muzzle Velocities were obtained with ETC Technology already in 1997 in the large Calibre Setup and a first Proof of Principle is performed

Result: First Proof of ETC Principle could be demonstrated successfully. Further Investigations with the 6.5l Firing Simulator and the 105mm ETC Demonstrator in 1998 for obtaining increased Performance will generate the Basics for 120mm ETC Gun Setup.

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EEF Follow-on Program - A Demonstration of Precision Ignition and Temperature Compensation in 120mm ETC Test Firings

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Armament Systems Division
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Electrothermal-Chemical Gun Propulsion
Aberdeen Proving Ground, Maryland
27 - 28 January 1998

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Outline

- US Army ETC Objectives
- Test Facility and Equipment
- Precision Ignition (M865)
- Temperature Compensation (DM13)
- Temperature Compensation (M829A2)
- Summary

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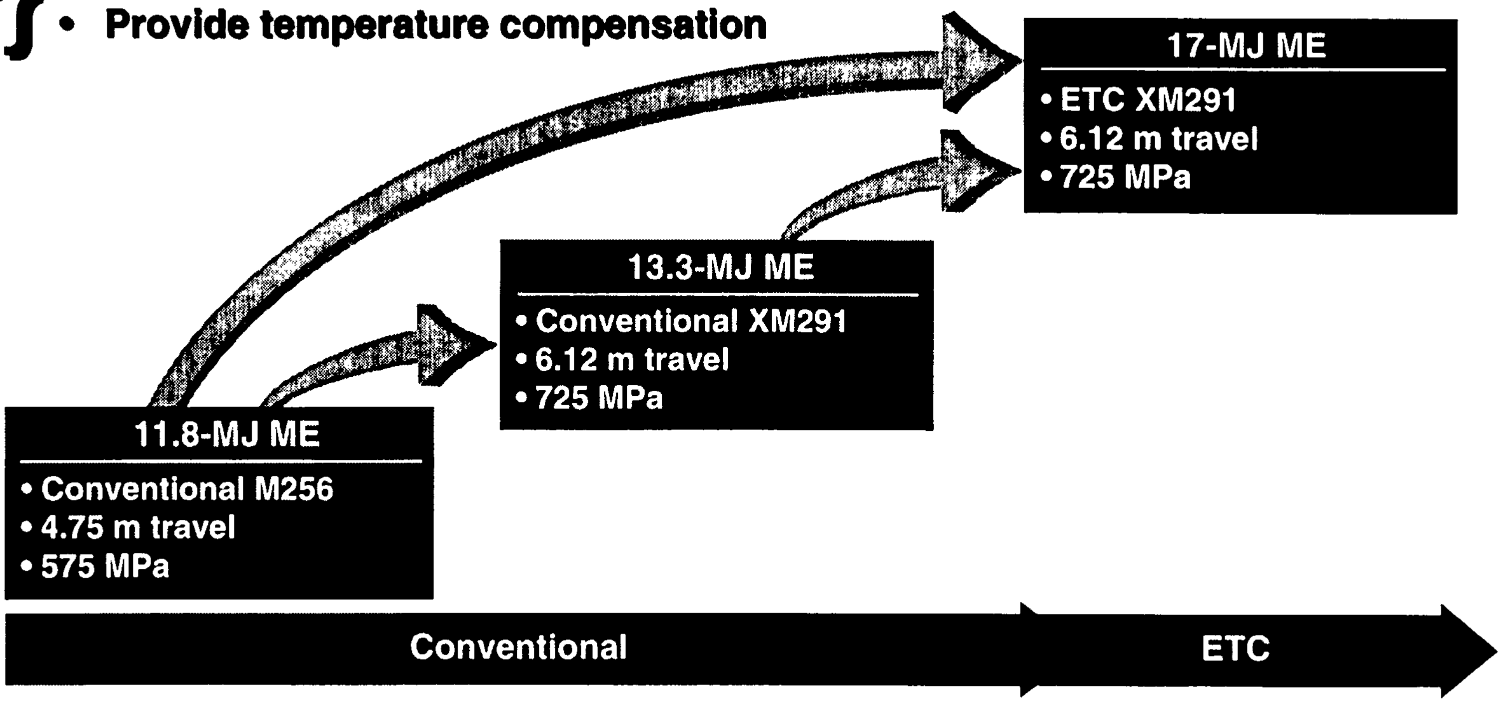
Army ETC Development

Objectives

- **Provide increased projectile muzzle energy over fielded conventional ammunition**
- **Maintain existing ammunition size**

EEF Follow-On Program }
- **Provide precise ignition timing**
- **Provide temperature compensation**



ETC technology offers the potential to significantly extend the performance window of conventional direct fire guns as well as provide precision ignition and temperature compensation.

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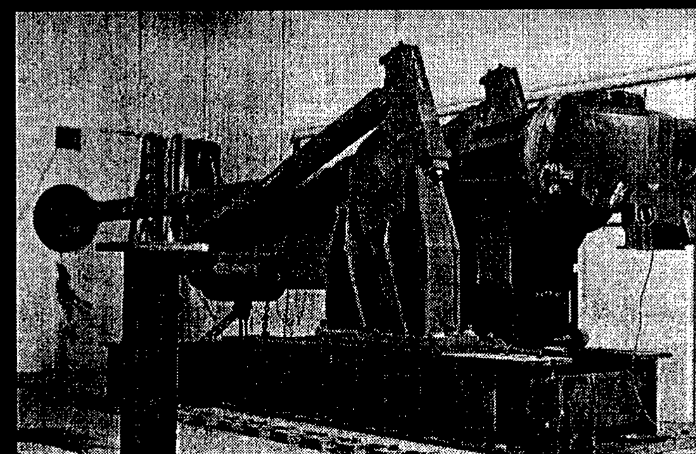
EEF Follow-on Program — Facility

Test Range

120 mm Test Fixture



The enclosed gun room at the United Defense Elk River test site provides safe, controlled test conditions, and is fully equipped with ballistic diagnostic instrumentation, including:

- In-bore pressure sensors
- Interior/exterior radar
- Voltage/current sensors
- High speed photography
- Flight analysis

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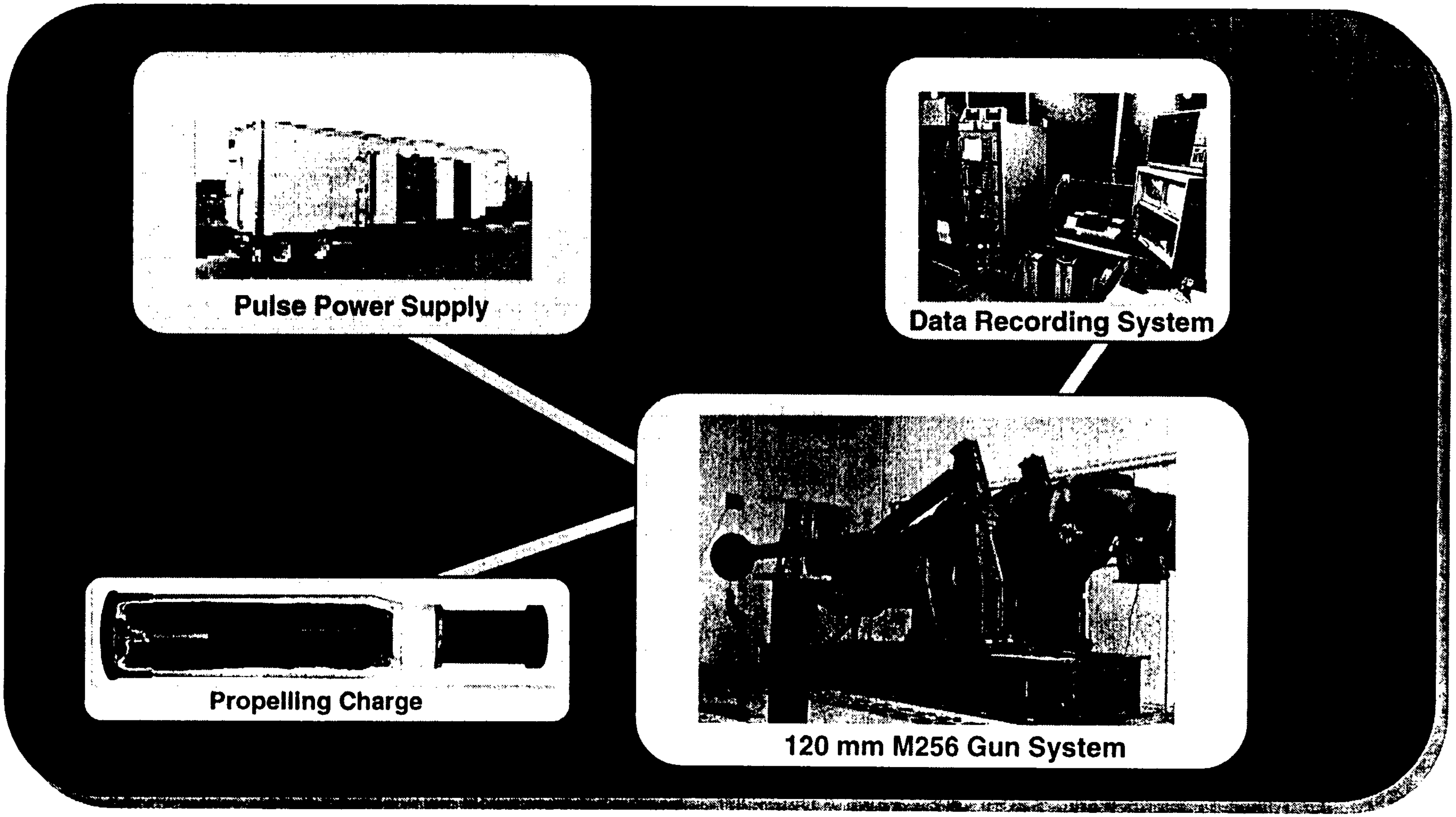
EEF Follow-on Program — Test Configuration



A fully integrated facility supports assembly, testing and data recording.

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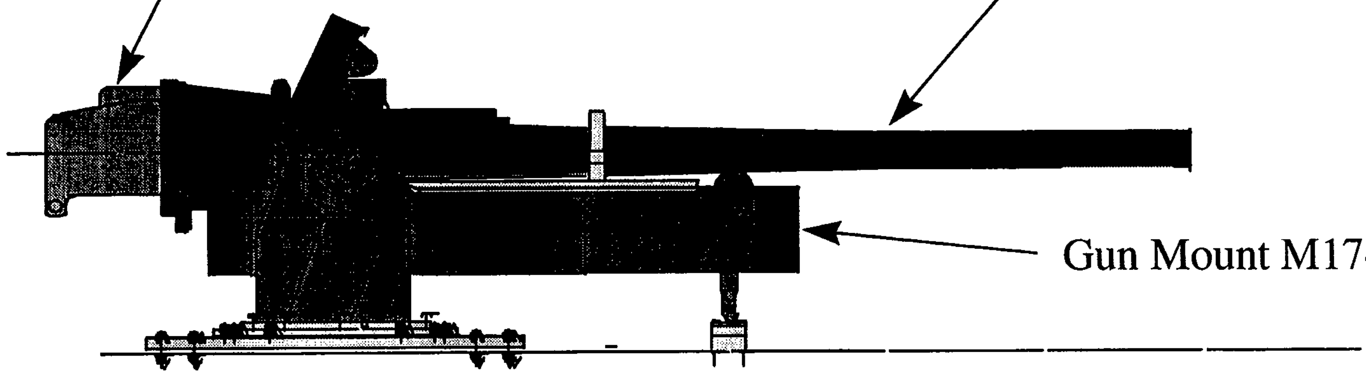
EEF Follow-on Program — Test Fixture



U.S. Army has provided the gun and mount assembly

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EEF Follow-on Program — Test Fixture

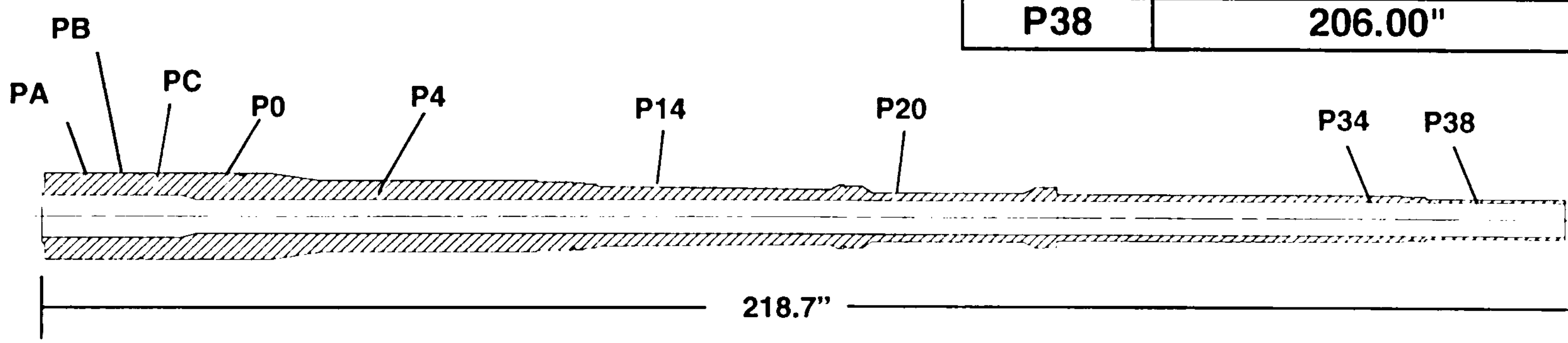
Gun: 120 mm M256

Travel: 4.75 m (39 cal)

Pressure: 575 MPa (ambient)
680 MPa (hot)

Volume: 9.4 L (ballistic)
8.5 L (propellant)

Pressure	Distance From Breech
PA40	3.75"
PA320	3.75"
PB45	11.75"
PB315	11.75"
PC60	19.25"
PC240	19.25"
P0	24.20"
P4	41.25"
P14	90.25"
P20	120.25"
P34	187.20"
P38	206.00"



Pressure transducers are mounted along the length of the chamber and bore.

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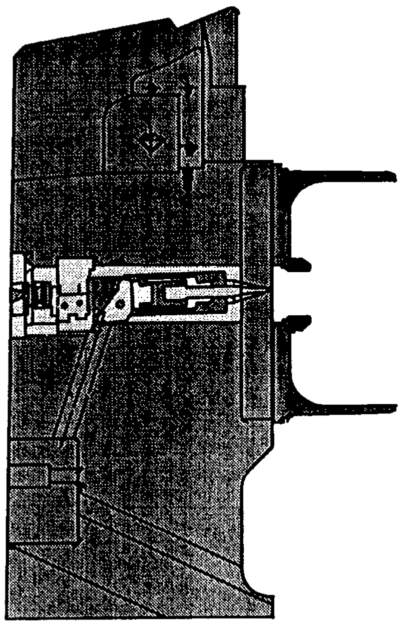
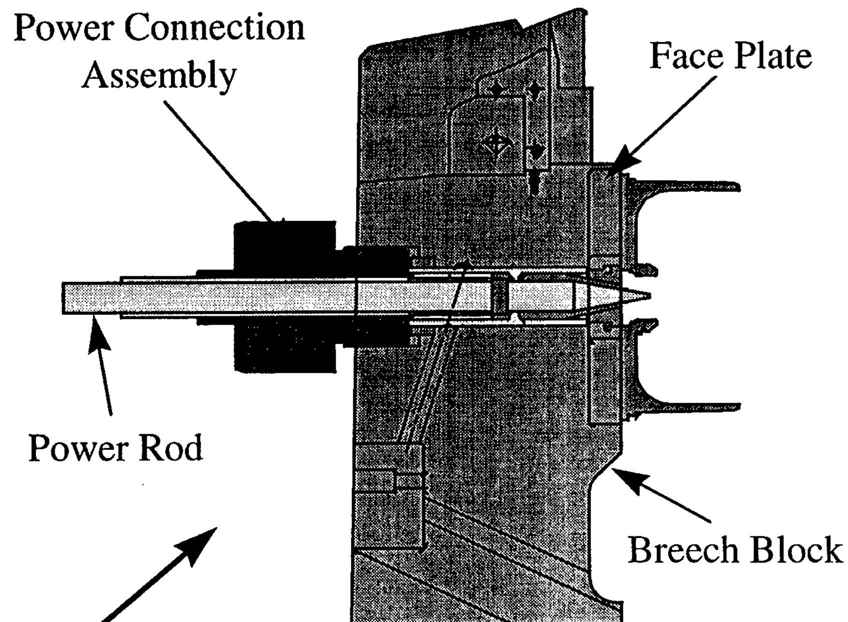
EEF Follow-on Program — Breech Blocks

Conventional Firing Pin



ETC Power Connection



ETC-modified breech block can be used for both conventional and ETC firings.

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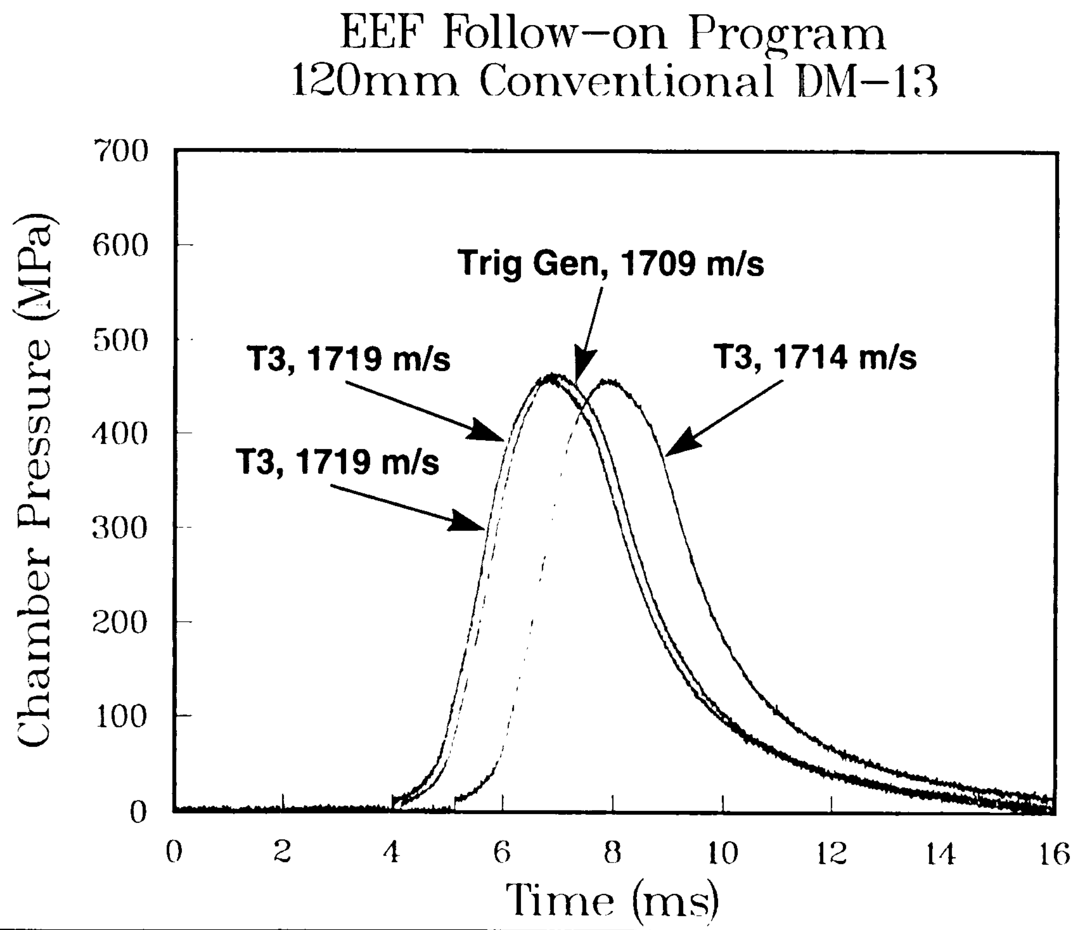
Temperature Compensation

Cold DM-13 with Conventional Primer:



Four cold DM13's have been fired with conventional primers.
Three were initiated with a standard T3 firing circuit.
One was initiated using the PFN trigger generator

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Precision Ignition

120mm M865 Round

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Precision Ignition — M865 Rounds

120-mm Test Objectives:

Demonstration	Gun System	Ignition Method	Ignition Energy	Ignition Delay Variation	Number of Shots
#1	120-mm	Benite Primer	~75 kJ	s.d. = measurement	10
#2	120-mm	Plasma Energy	75 - 150 kJ	s.d. < demo #1	10

ETC plasma energy should provide a smaller ignition delay variation than that of a conventional igniter.

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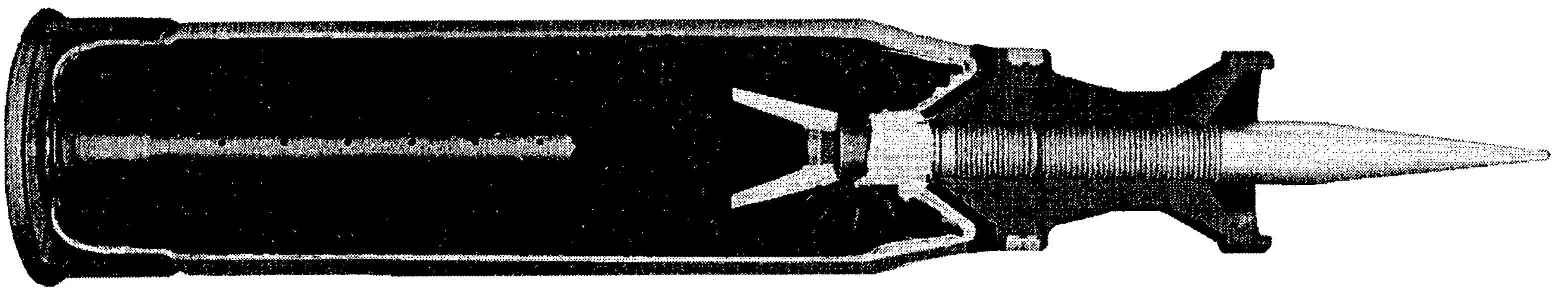
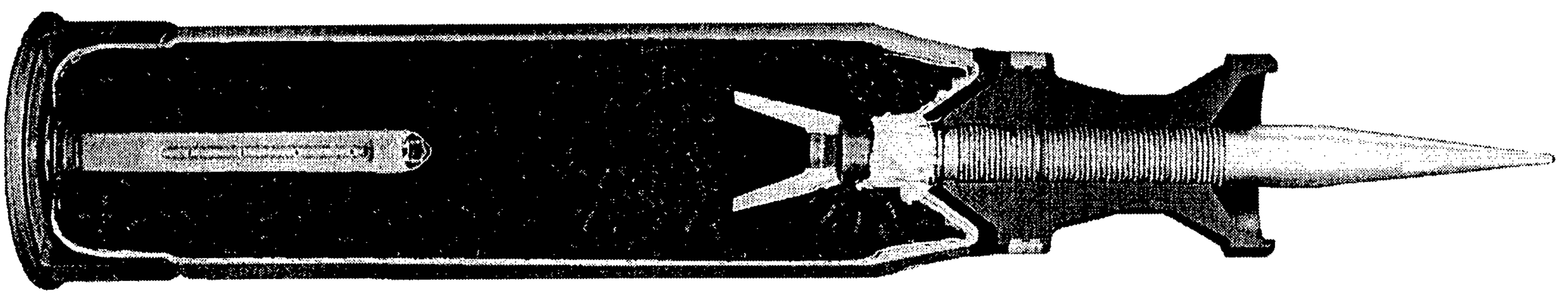
Precision Ignition — M865 Rounds

Conventional M865 Round with M125 Benite Primer*



*Approximate chemical energy of primer is 75 kJ.

ETC M865 Round with Plasma Injector



- Propellant Type: LKL (19 perf)
- Loading density: 0.8 g/cc
- Propellant Mass: 7.87 kg
- Projectile/Sabot Mass: 5.825 kg

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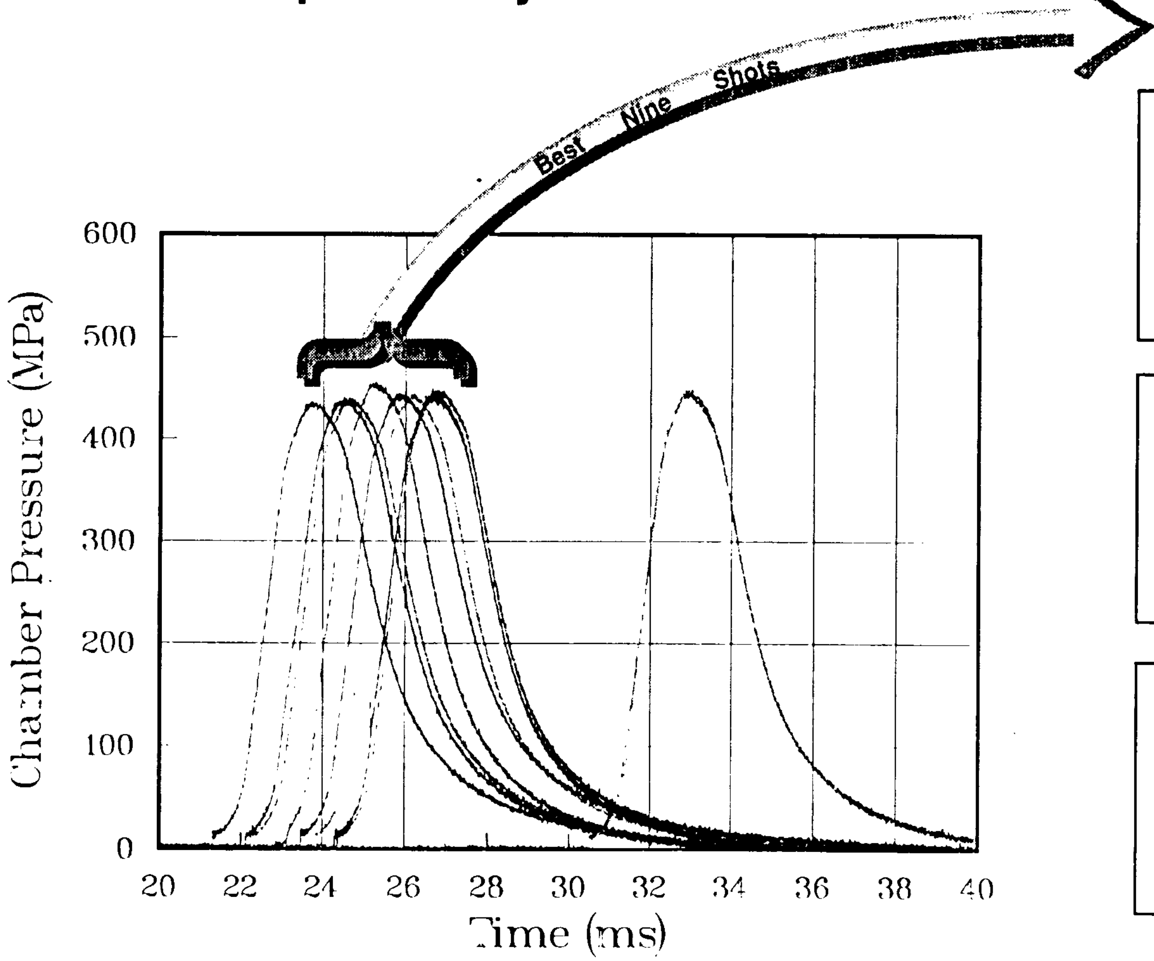
Precision Ignition — Conventional Firings

11 Shot Repeatability Series:



Statistical Analysis
(Best Case)

T2 (trigger to 40 MPa)

Mean	=	23.777 ms
Sigma	=	1.108 ms

T4 (trigger to exit)

Mean	=	30.218 ms
Sigma	=	1.093 ms

Velocity

Mean	=	1778 m/s
Sigma	=	11.52 m/s

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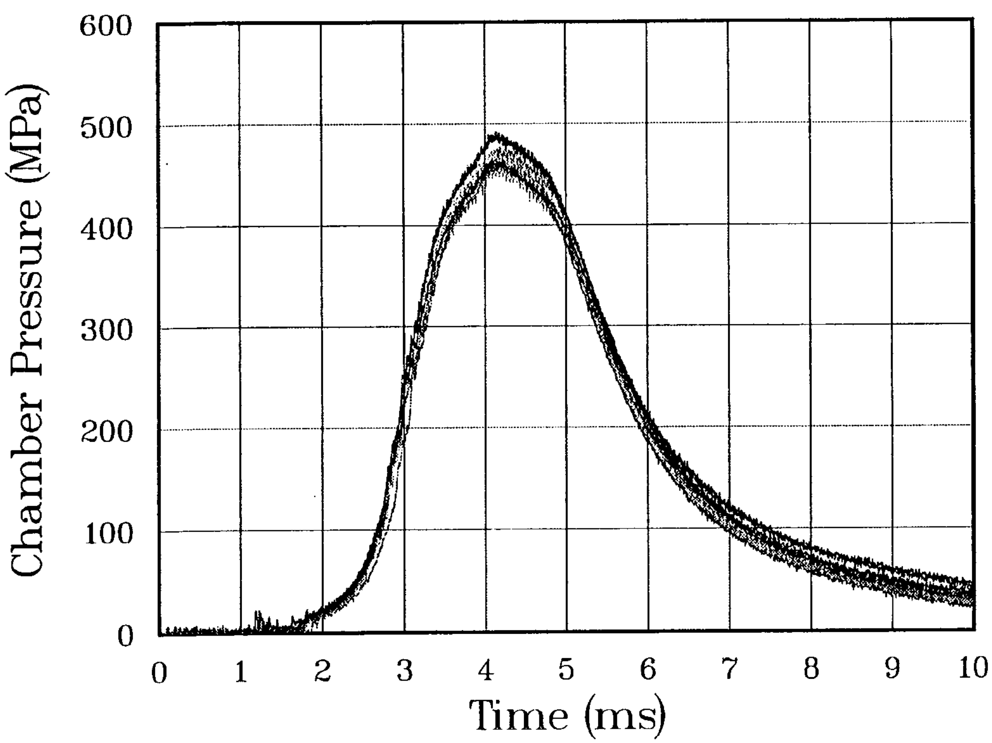
Precision Ignition — ETC Firings

10 Shot* Repeatability Series:



Statistical Analysis (10 shots)

T2 (trigger to 40 MPa)

Mean	=	2.355 ms
Sigma	=	0.0418 ms

T4 (trigger to exit)

Mean	=	8.796 ms
Sigma	=	0.0441 ms

Velocity

Mean	=	1766 m/s
Sigma	=	9.20 m/s

*11 shots were conducted. Pressure transducer signal was lost on one shot.

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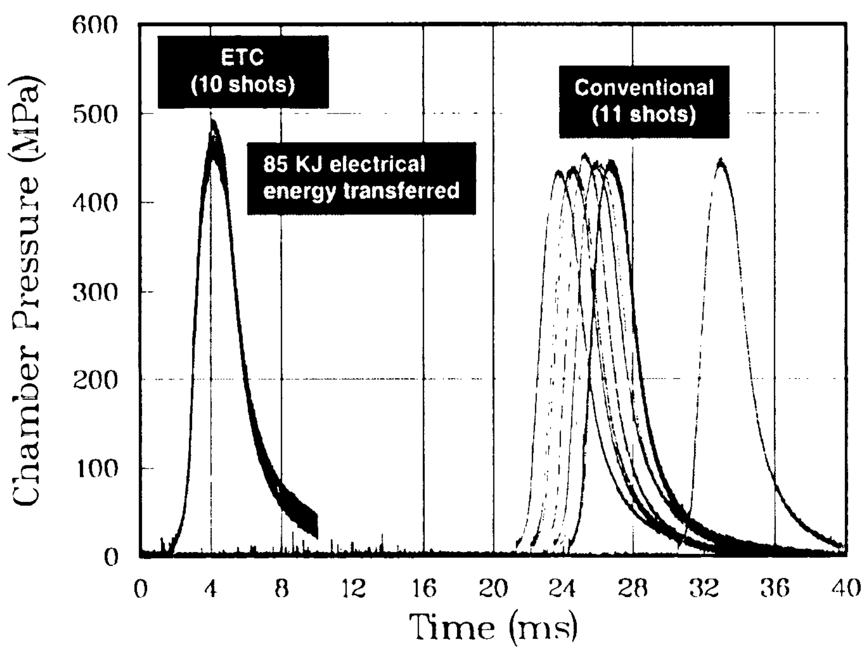
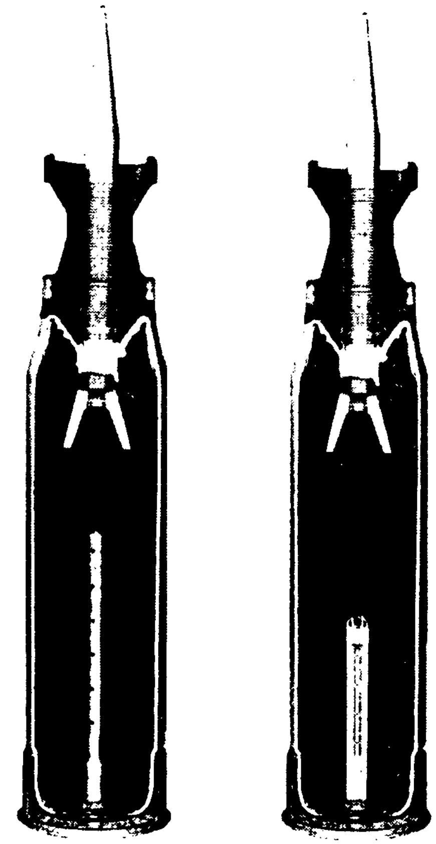
Precision Ignition — Summary of Firings

ETC Precision Ignition: 120 mm M865 Round





Conventional M865 Round with M125 Benite Primer

ETC M865 Round with Plasma Injector

Test series complete 30 April 96

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Precision Ignition - M865 Summary

Repeatability Results:

	T2 (ms)		T4 (ms)		Velocity (m/s)	
	Mean	Sigma	Mean	Sigma	Mean	Sigma
Conventional Ignition						
- Best Case	23.777	1.108	30.218	1.093	1778	11.52
- Worst Case	25.117	3.141	31.553	3.127	1779	10.73
ETC Ignition	2.355	0.0418	8.796	0.0441	1766	9.20

ETC firings reduced T2 standard deviation by a factor of 26

Temperature Compensation

120mm DM13 Round

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Temperature Compensation — DM13 Approach

Objective:

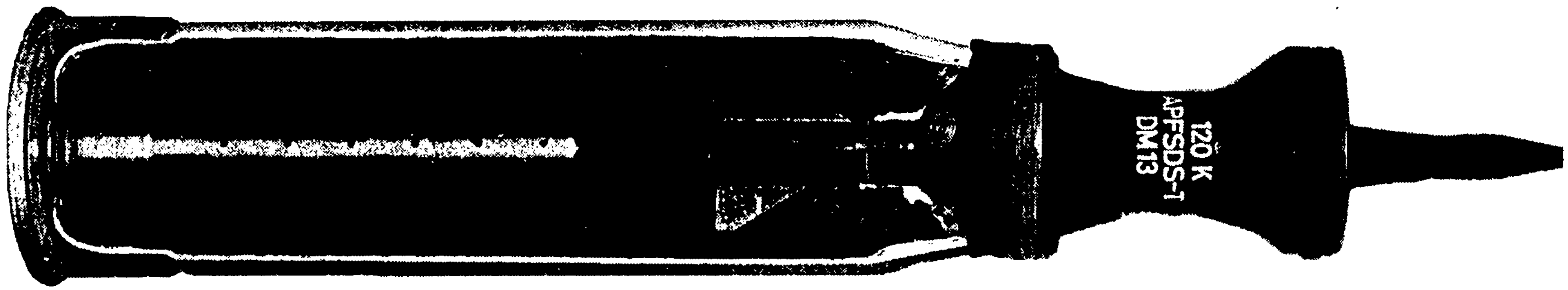
Demonstrate hot conventional performance with ambient ETC ignition

Plan:

- Design plasma injector to incorporate into DM13 120-mm round
- Fire nine rounds conventionally; three at each temperature condition: cold, ambient, and hot
- Conduct systematic test series to identify power and energy configuration that gives hot round performance at ambient temperature
- Conduct ten shot repeatability series with this configuration

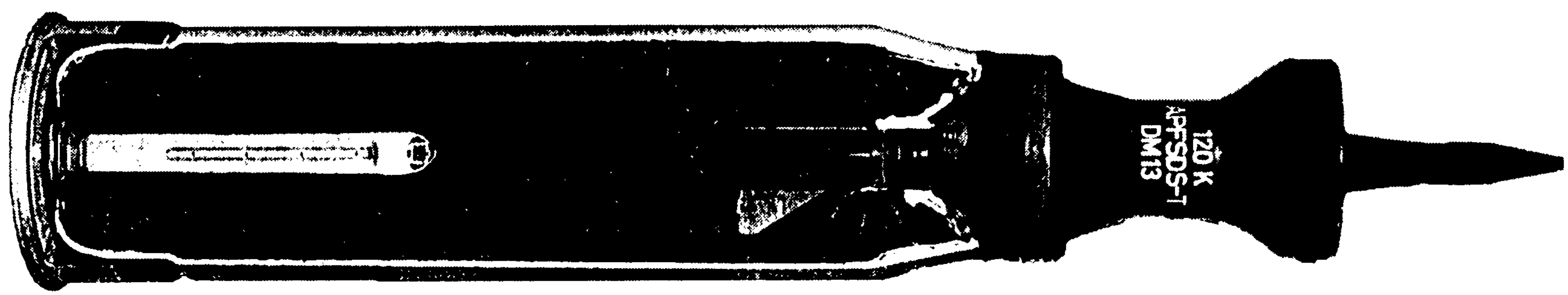
Temperature Compensation — DM13 Rounds

Conventional DM-13 Round with M125 Benite Primer*



*Approximate chemical energy of primer is 75 kJ.

ETC DM-13 Round with Plasma Injector



- Propellant Type: JA2 (7 perf)
- Loading Density: 0.75 g/cc
- Propellant Mass: 7.345 kg
- Projectile/Sabot Mass: 7.11 kg

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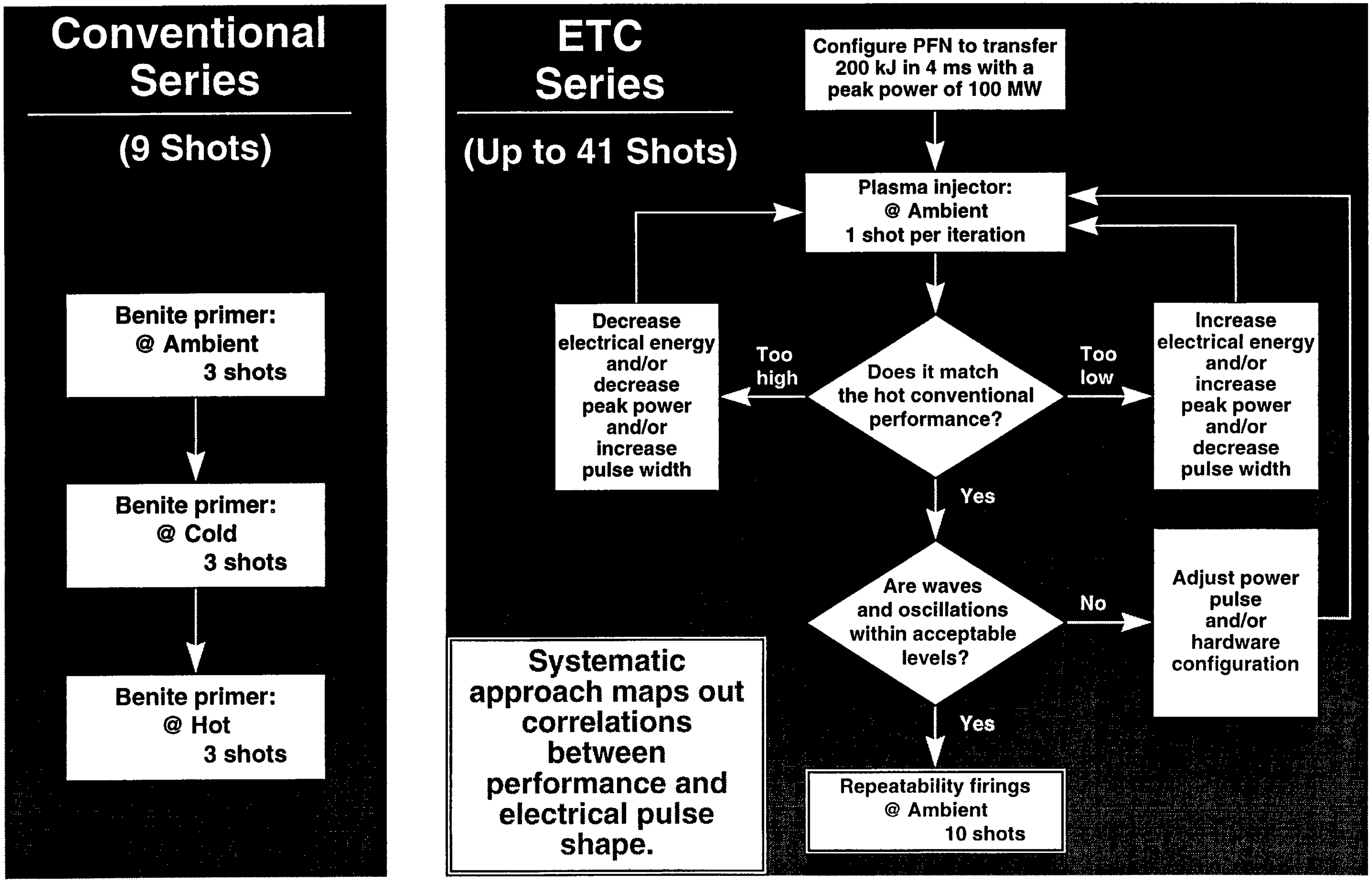
Temperature Compensation — Test Plan



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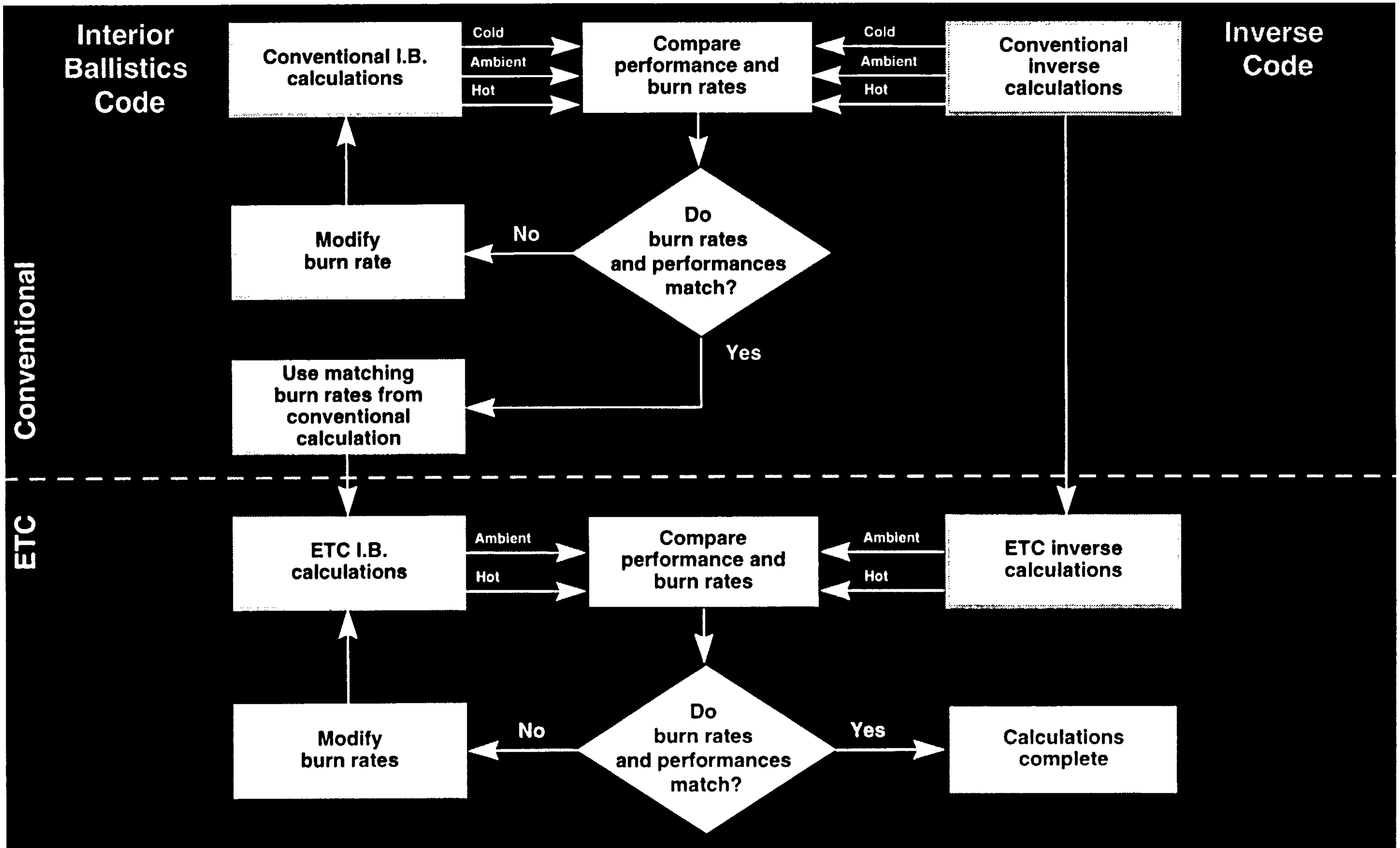
Temperature Compensation — Analysis



I.B. and inverse analyses will help determine what effect (if any) ETC ignition has on propellant burn rate

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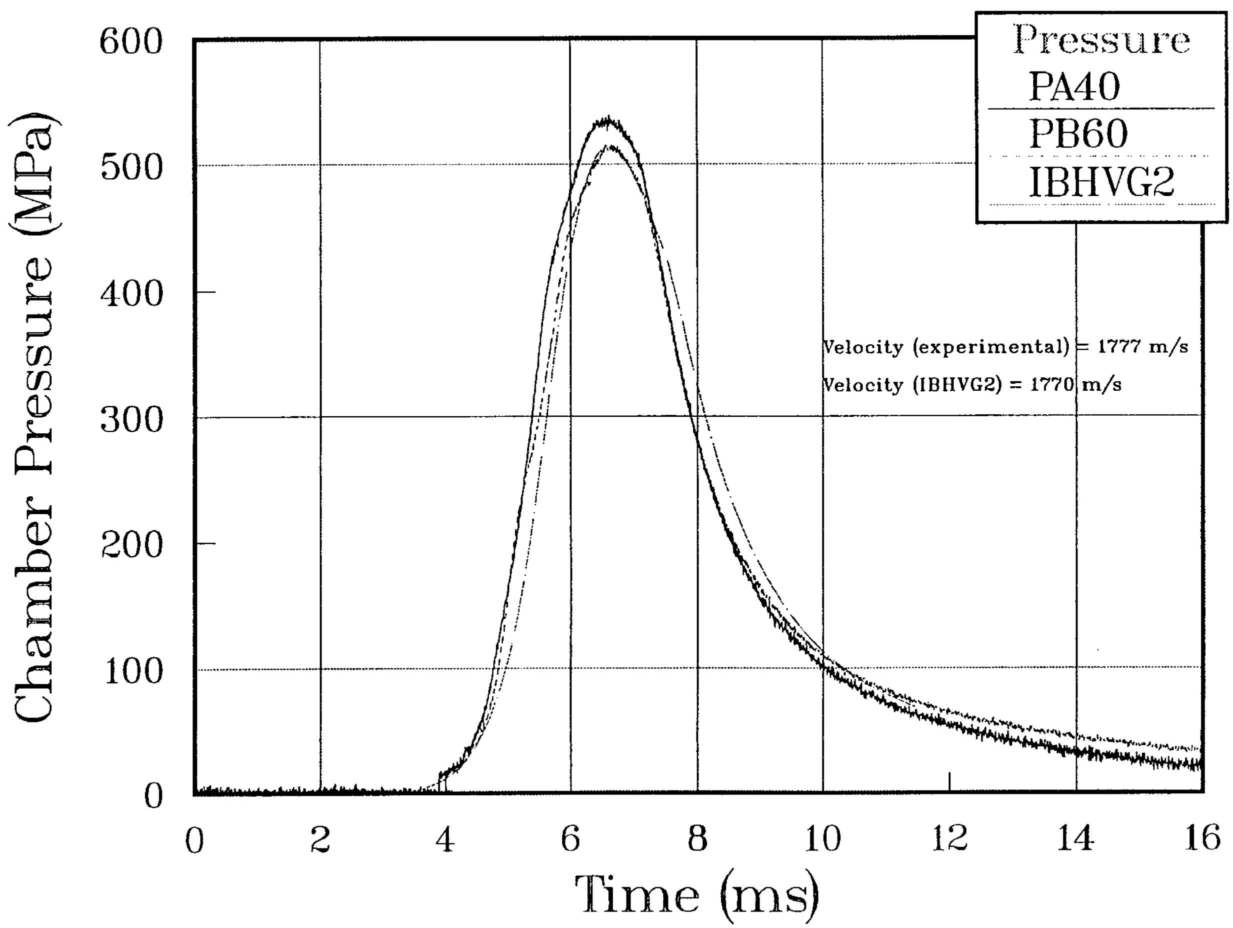
Temperature Compensation — Prediction vs. Test

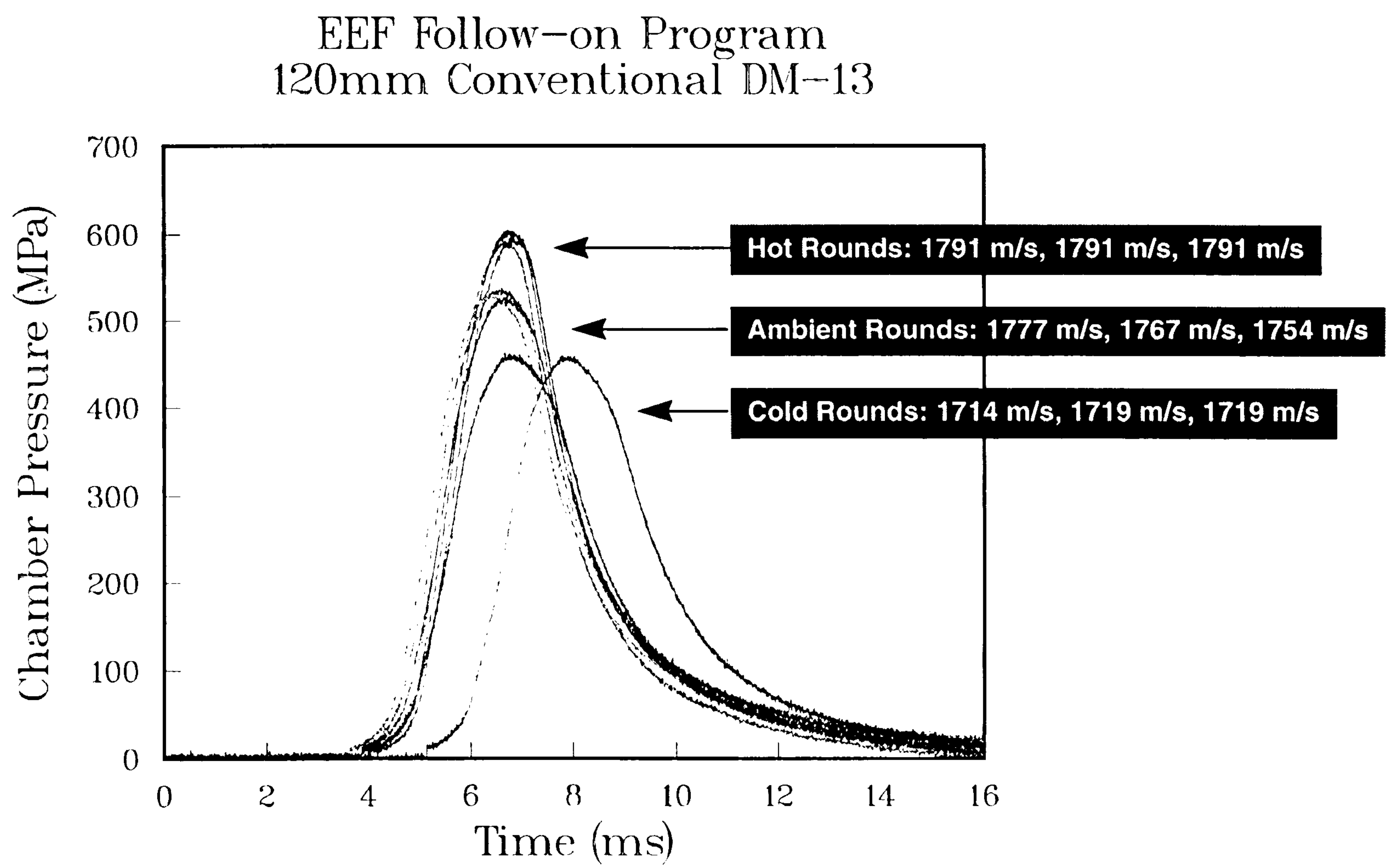
EEF Follow–on Program
120mm Shot #39 – DM13 Round



Computer prediction matches ambient conventional firing

Temperature Compensation — Conventional

Baseline Firings:



Three rounds were fired conventionally at each of three temperature conditions: 47 deg C, 21 deg C, and 0 deg C (Total of nine shots).

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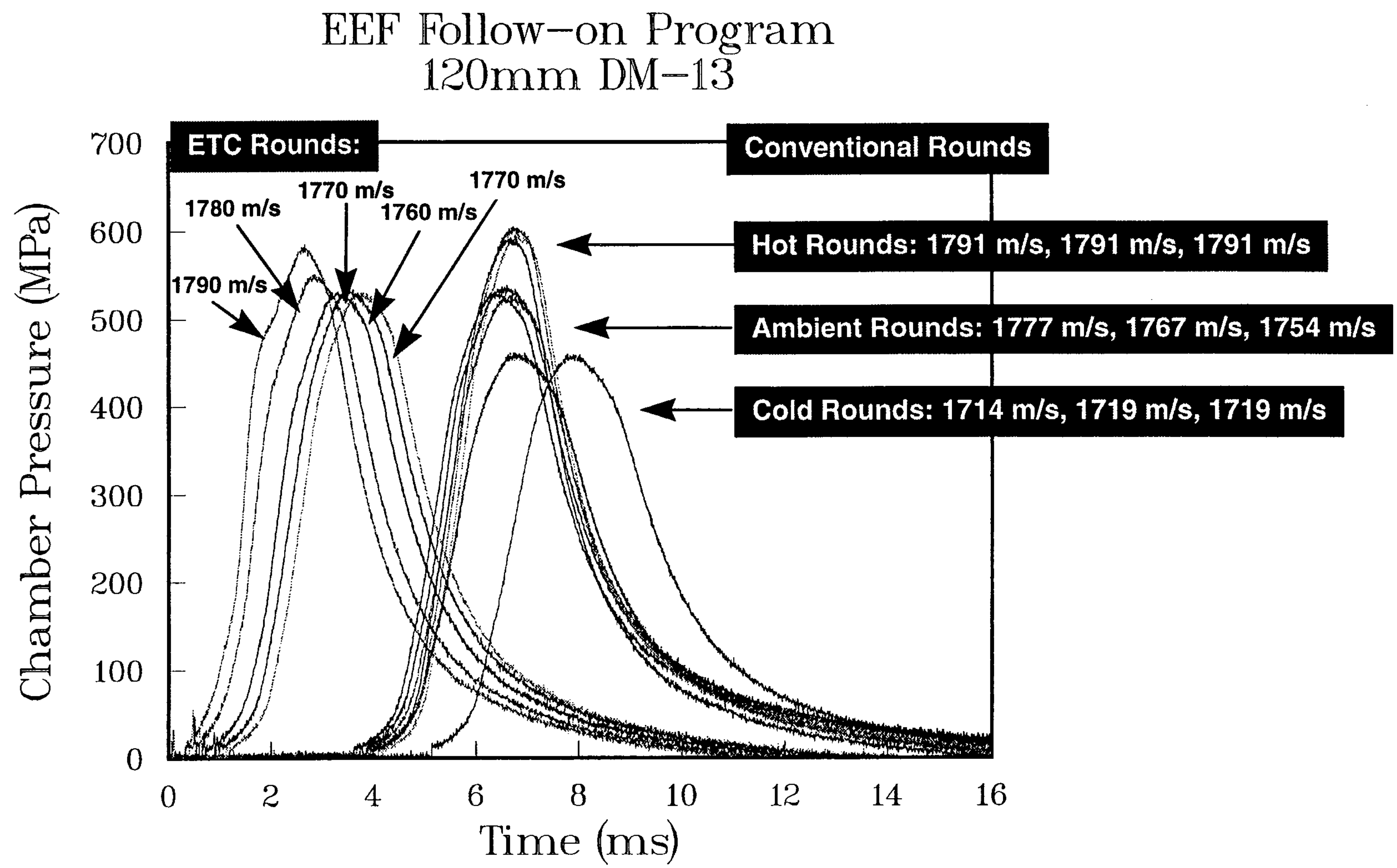
Temperature Compensation — Conventional & ETC



Three rounds were fired conventionally at each of three temperature conditions: 47 deg C, 21 deg C, and 0 deg C (Total of nine shots). Five ambient ETC tests show walkup in performance.

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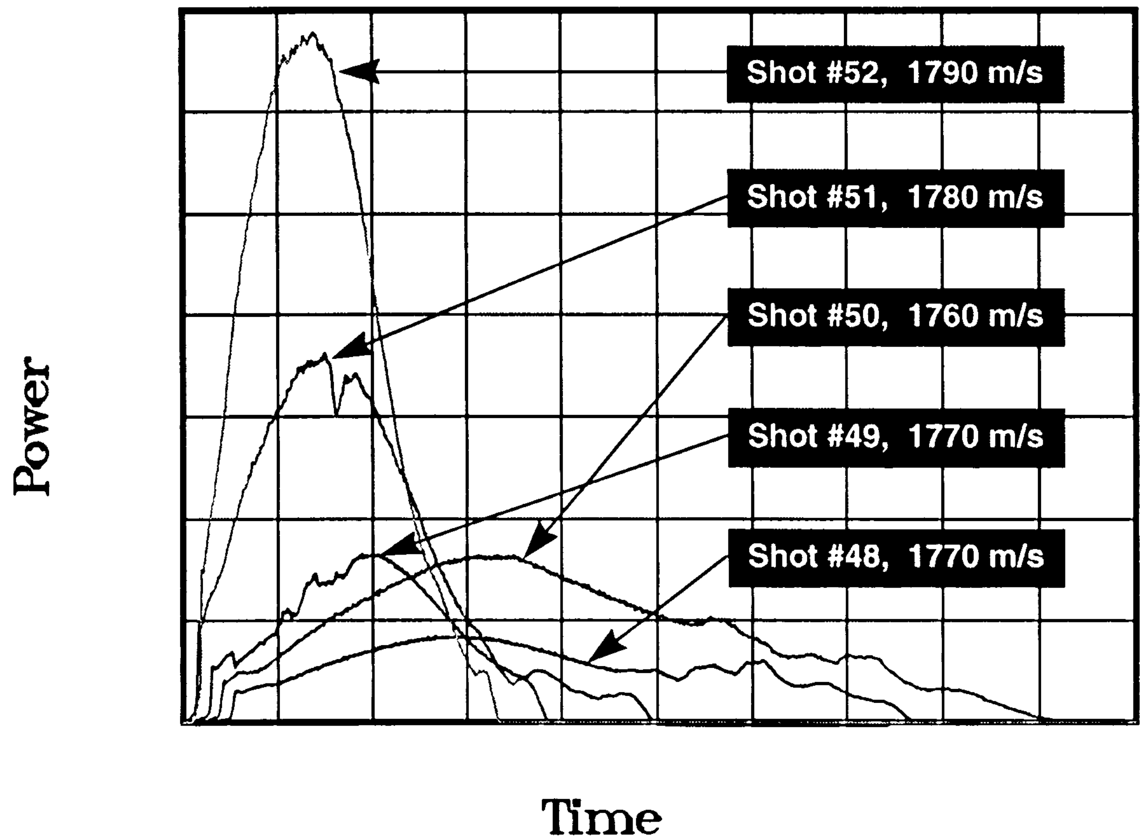
Temperature Compensation — Power

120mm ETC Firings:

EEF Follow-on Program
DM-13 ETC Power Profiles



A fast, high power electrical pulse is needed to achieve "hot round" performance (1791 m/s).

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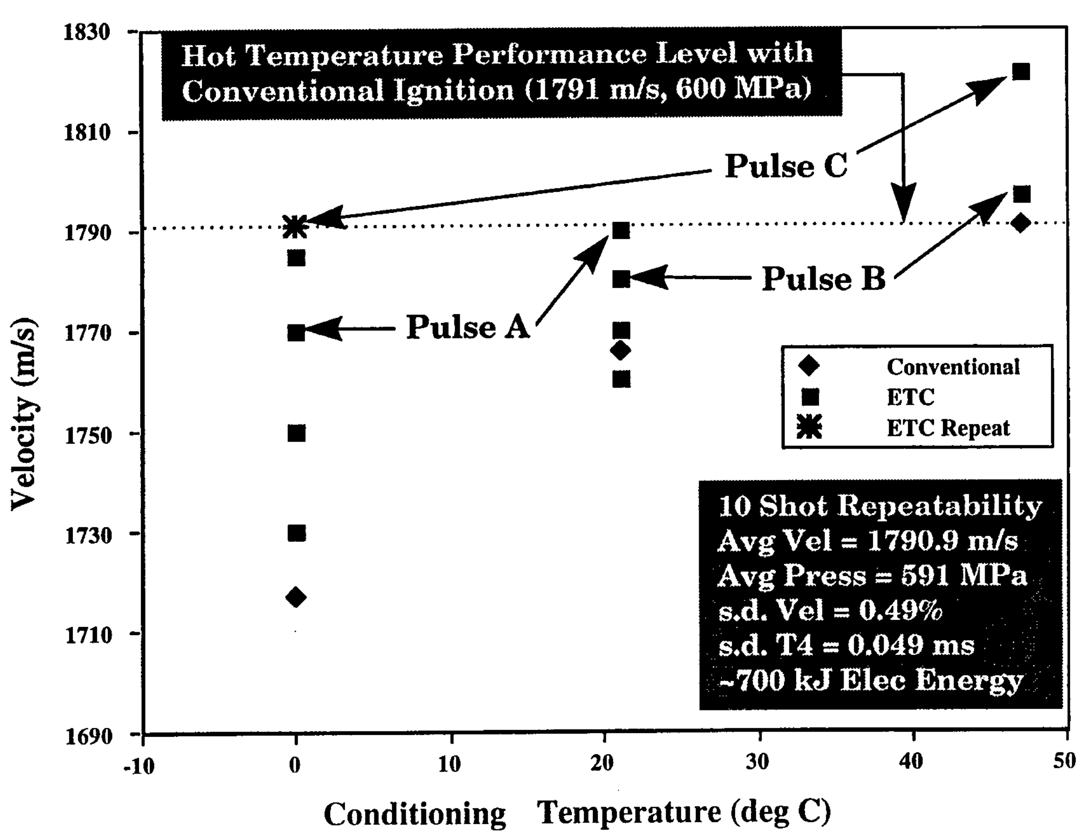
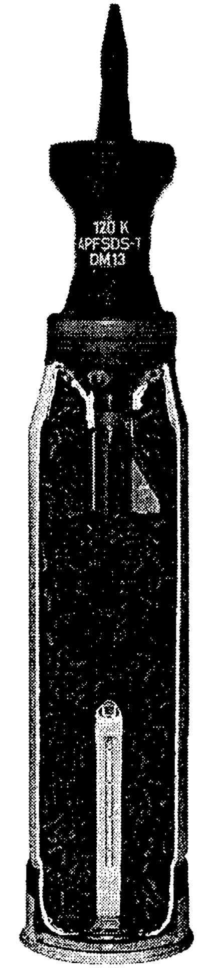
Temperature Compensation — DM13 Summary

Temperature Compensation 120 mm ETC Ignition of DM13



Conventional DM-13 Round with M125 Benite Primer



ETC DM-13 Round with Plasma Injector

Hot round performance (1791 m/s) has been achieved in both ambient and cold rounds using less than 700 kJ

Temperature Compensation

120mm M829A2 Round

M829A2 Temperature Compensation - Approach

Objective:

Demonstrate hot conventional performance with ETC ignition in ambient, cool, and cold M829A2 rounds.

Plan:

- Design plasma injector to incorporate into M829A2 120-mm round.
- Establish conventional baseline performance by firing at each temperature condition, cold (-32C), ambient (21C), and hot (49C), using conventional ignition.
- Conduct systematic test series to identify power and energy configuration that gives hot performance at ambient (21C) temperature.
- Similarly, identify power and energy configuration that gives hot performance at cool (0C) temperature.
- Complete series by testing at cold temperatures down to -32C in an attempt to match hot performance.

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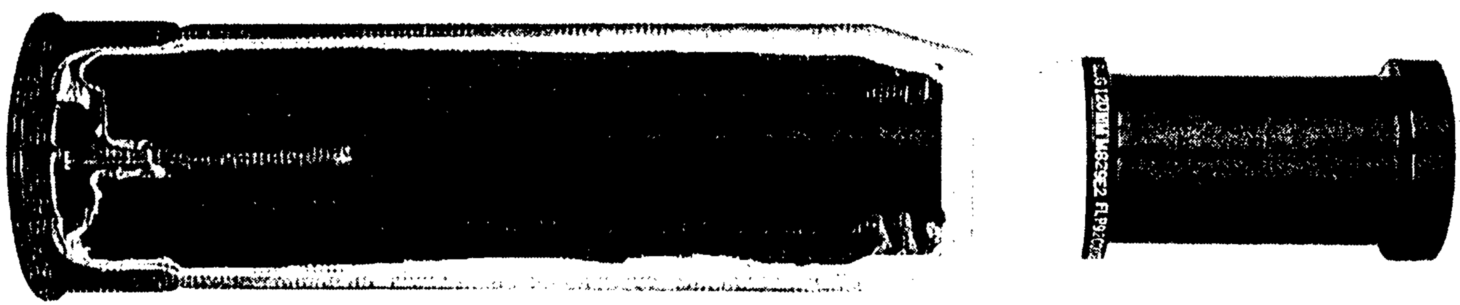
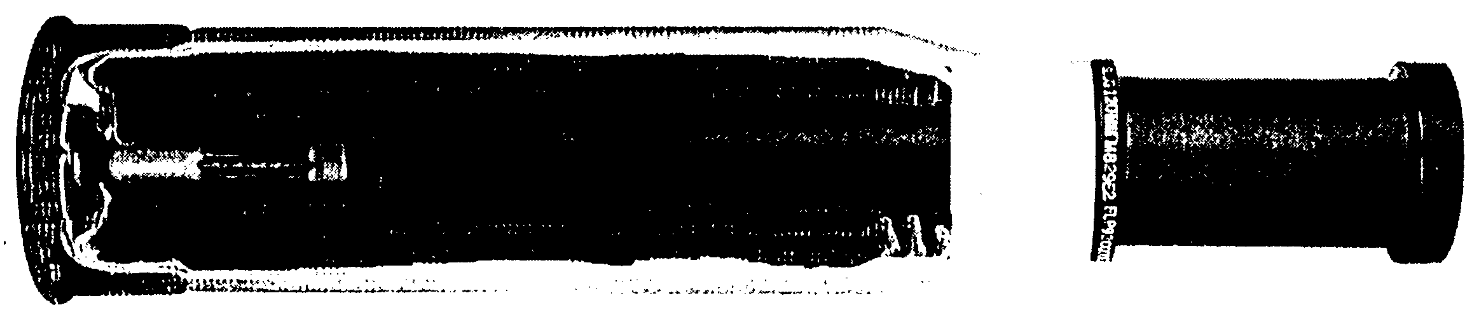
Temperature Compensation — M829A2 Slug Rounds

Conventional M829A2 Slug Round with M129 Benite Primer*



*Approximate chemical energy of primer is 75 kJ.

ETC M829A2 Slug Round with Plasma Injector



- Propellant Type: JA2 Stick
- Loading Density: 0.92 g/cc
- Propellant Mass: 8.55 kg
- Launch Mass: ~7.78 kg

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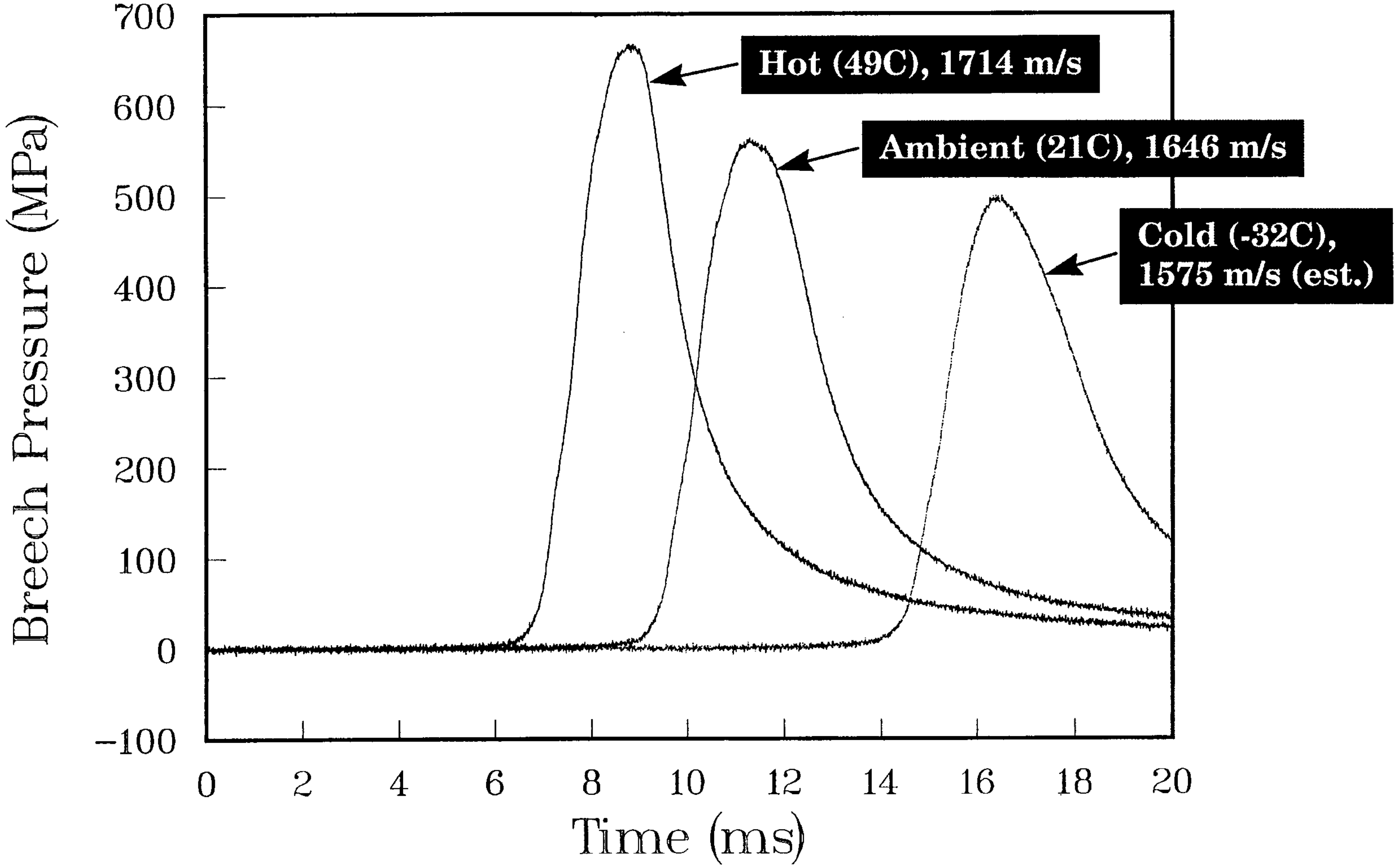
Temperature Compensation — Conventional



Using conventional ignition, two rounds were fired at 49C, one round was fired at 21C, and one round was fired at -32C.

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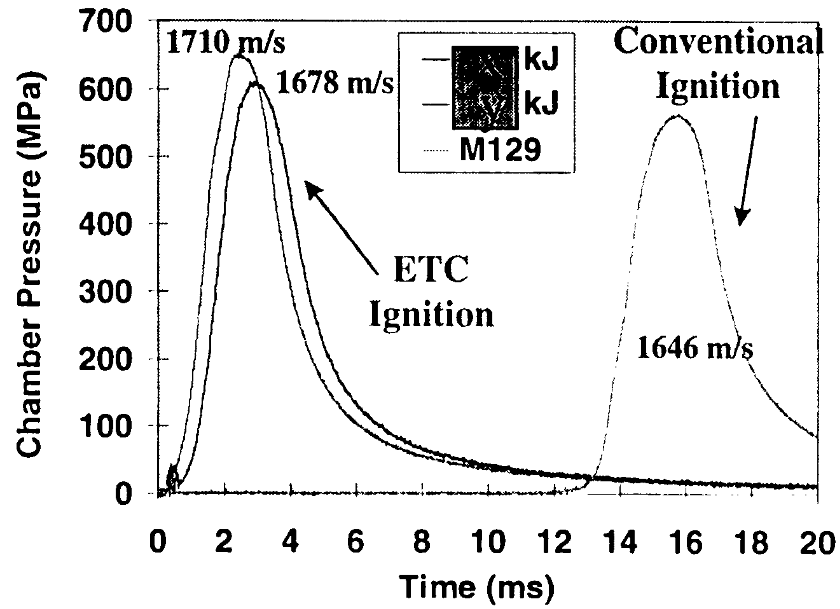
Temperature Compensation — Ambient ETC

Ambient (21C) Firings



With ETC ignition, performance increases with energy, peak power, and power rise rate. In addition, ignition delay time is greatly reduced.

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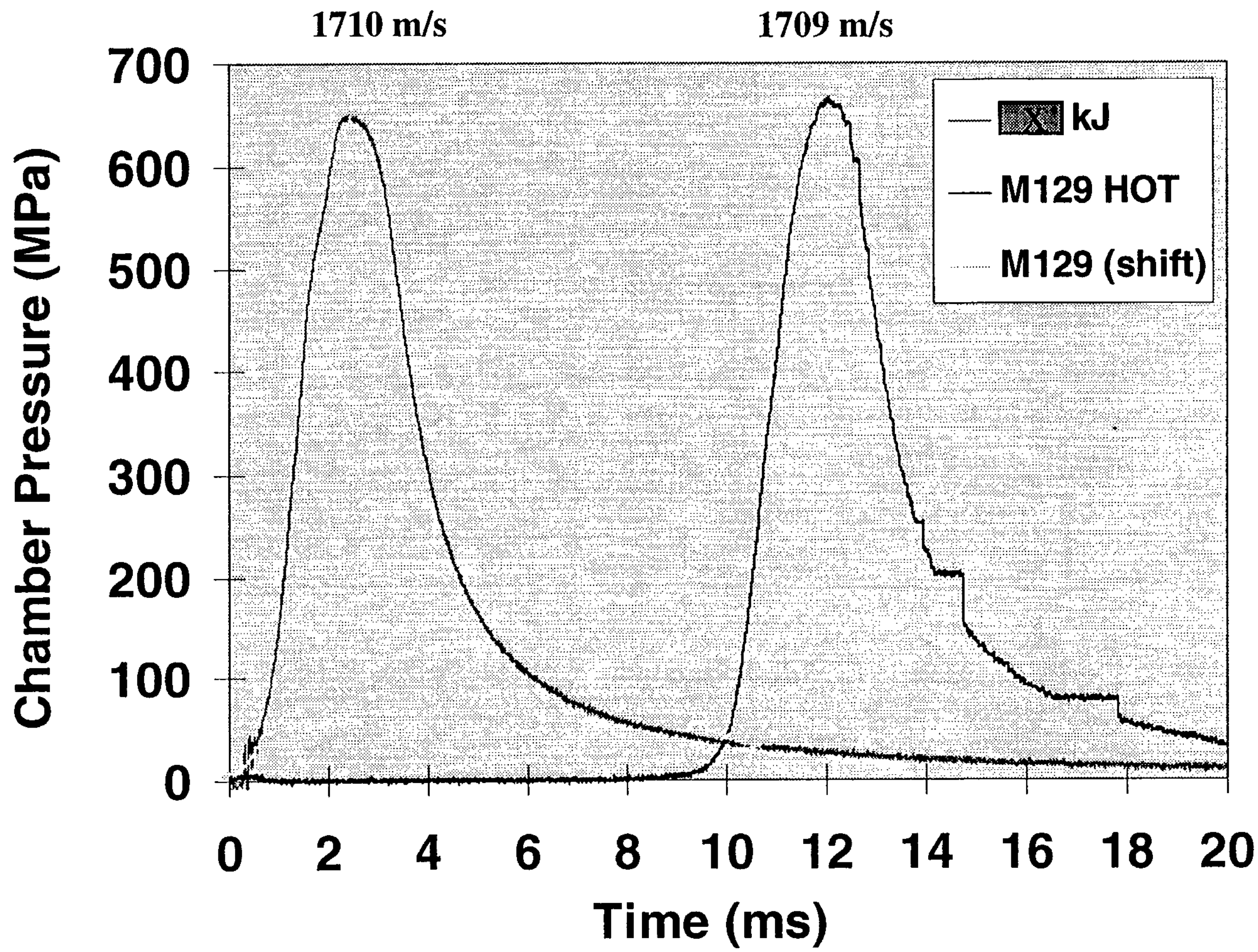
Temperature Compensation - Hot Performance

Ambient ETC vs. Hot Conventional



The ambient ETC pressure profile closely matches that of the hot conventional (shifted in time).

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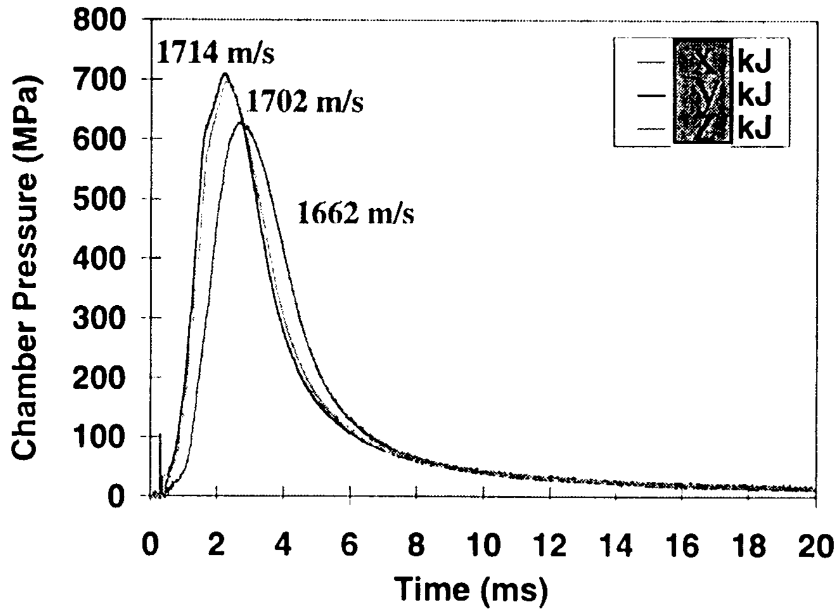
Temperature Compensation — Cool ETC

Cool (0C) Firings



A fast, high power electrical pulse is needed to achieve "hot round" performance (1714 m/s). However, additional energy later in the electrical power pulse does not necessarily benefit performance.

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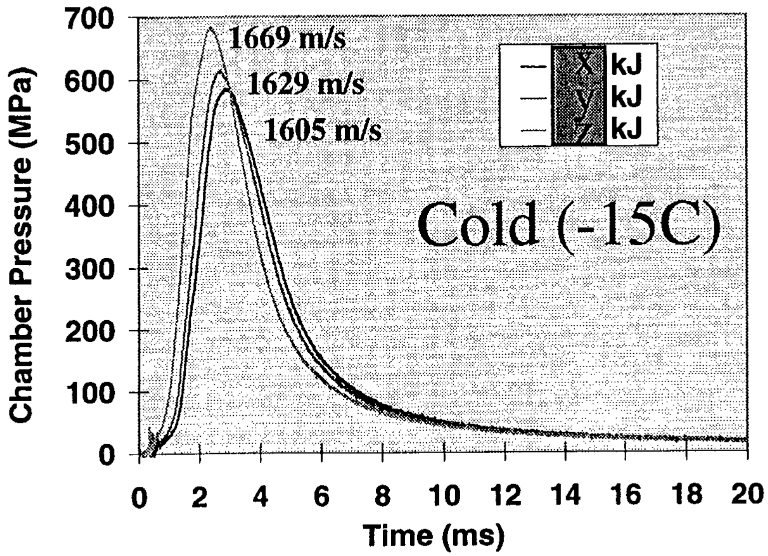
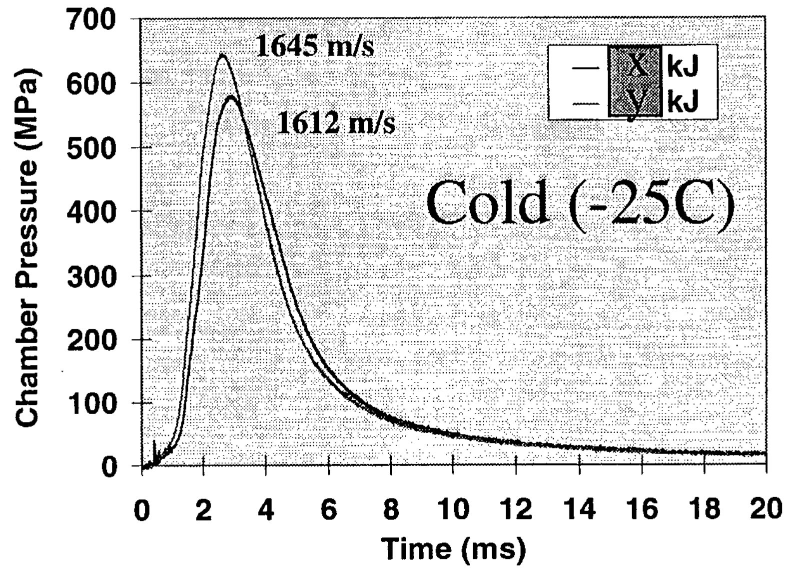
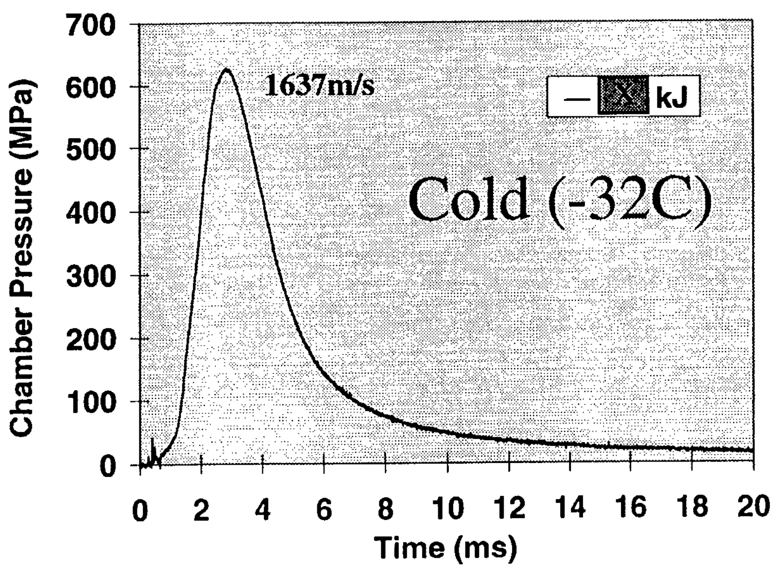
Temperature Compensation — Cold ETC







Performance increases with electrical energy at a given temperature as expected. However, performance also increases with decreasing temperature for a fixed electrical energy input.

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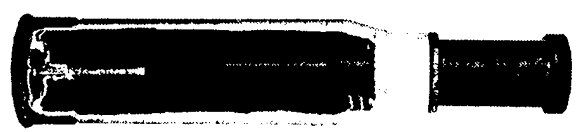
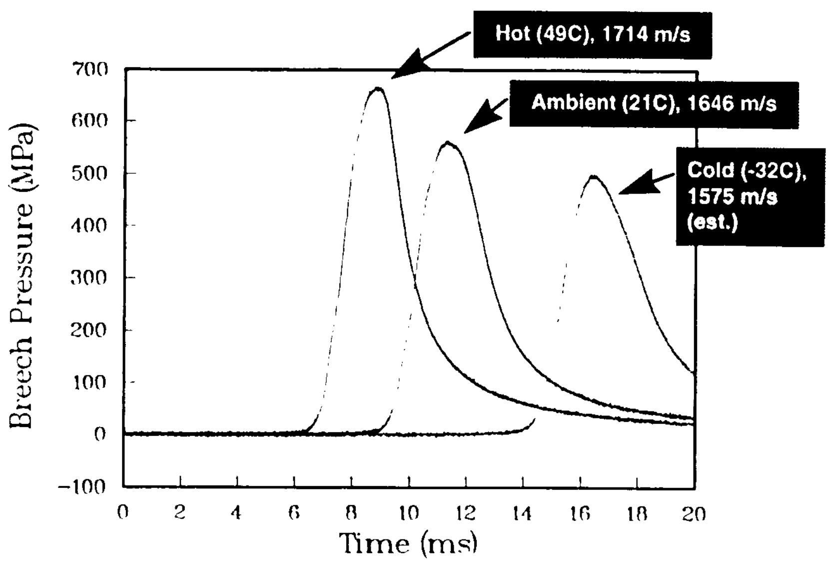
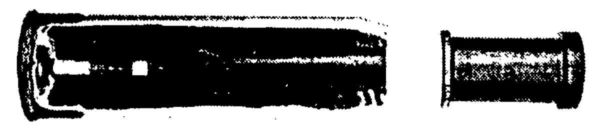
Temperature Compensation — M829A2 Summary

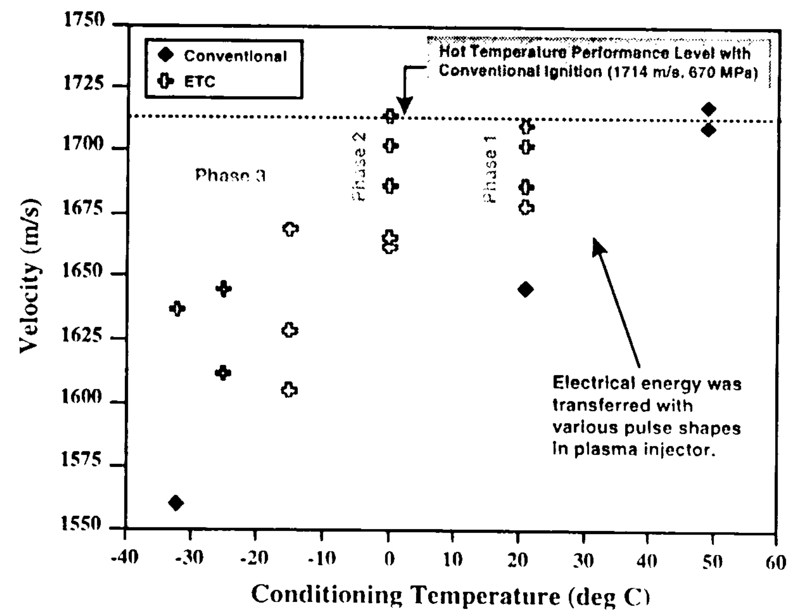
Conventional M829A2 Slug Round





ETC Modified M829A2 Slug Round





- **Propellant Load:**
  - 8.55 Kg JA2 Stick Propellant
  - 0.70 Kg Combustible Case
- **Launch Mass:** ~ 7.78 kg
- **Ballistic Volume:** ~ 9.37 liters
- **Projectile Travel:** 4.75 meters (39 cal)

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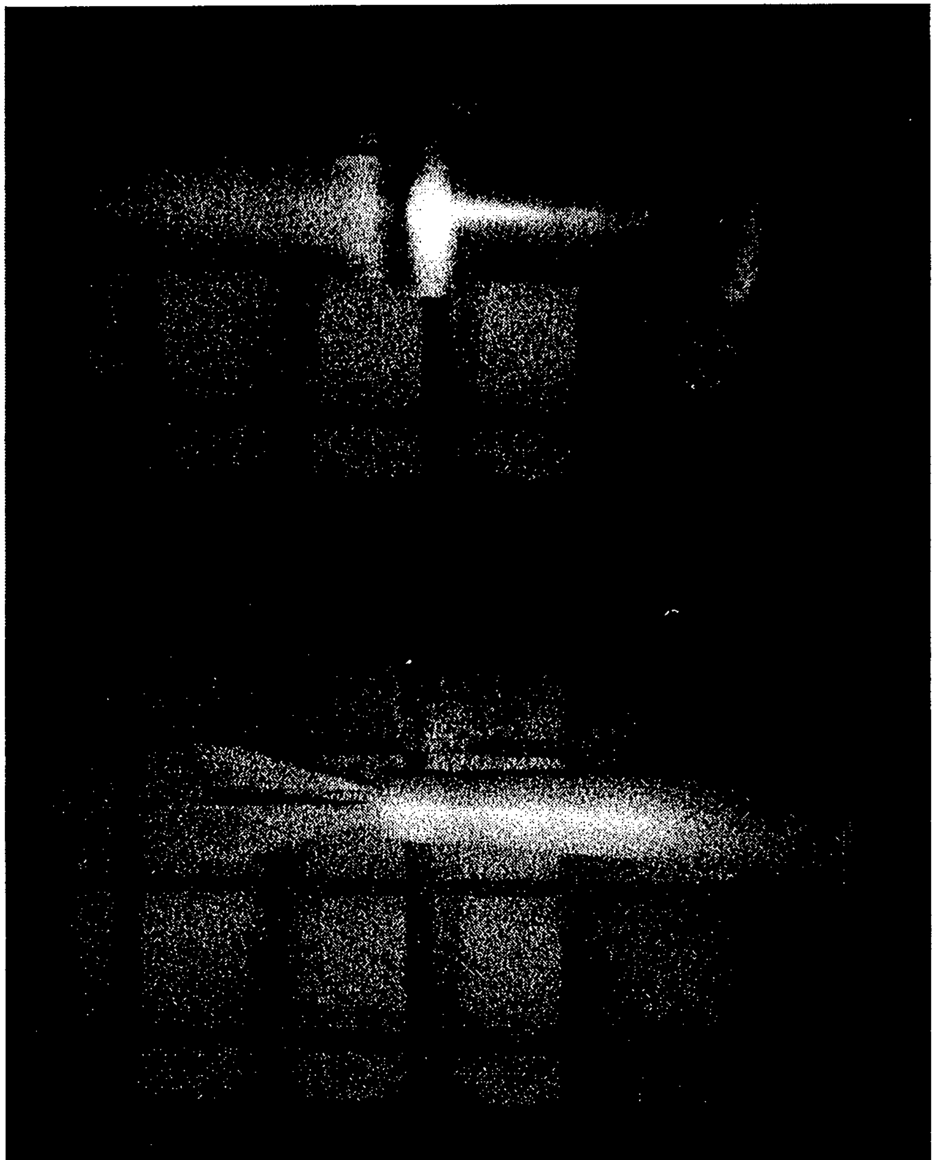
Temperature Compensation — Fin Integrity



- High speed Cordin camera operating at 50,000 frames per second shows forward slug section and afterbody with fins
- Projectile image was captured in-flight approximately 50 feet downrange from muzzle
- Fins appear to be undamaged

High speed photography reveals that fins remain intact after ETC ignition cycle.

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Temperature Compensation - Concluding Remarks

Summary

- An electrical power pulse delivering less than 500 kJ brought an ambient round up to the hot round level of performance (at lower pressure).
- A cool round needed an electrical energy transfer of less than 500 kJ to achieve hot round performance as well; however, pressure was higher.
- Colder temperatures down to -32C have demonstrated ETC induced performance increases. In fact, rounds at the colder temperatures appear to be more enhanced for a given power pulse.
- Plasma ignition at these energy levels does not appear to be detrimental to the structural integrity of the projectile afterbody.

The ability to compensate for varying temperatures using ETC ignition has been demonstrated in the M829A2 slug round. Future work should include efforts to complete the cold test series for this JA2 stick configuration as well other advanced propellant systems.

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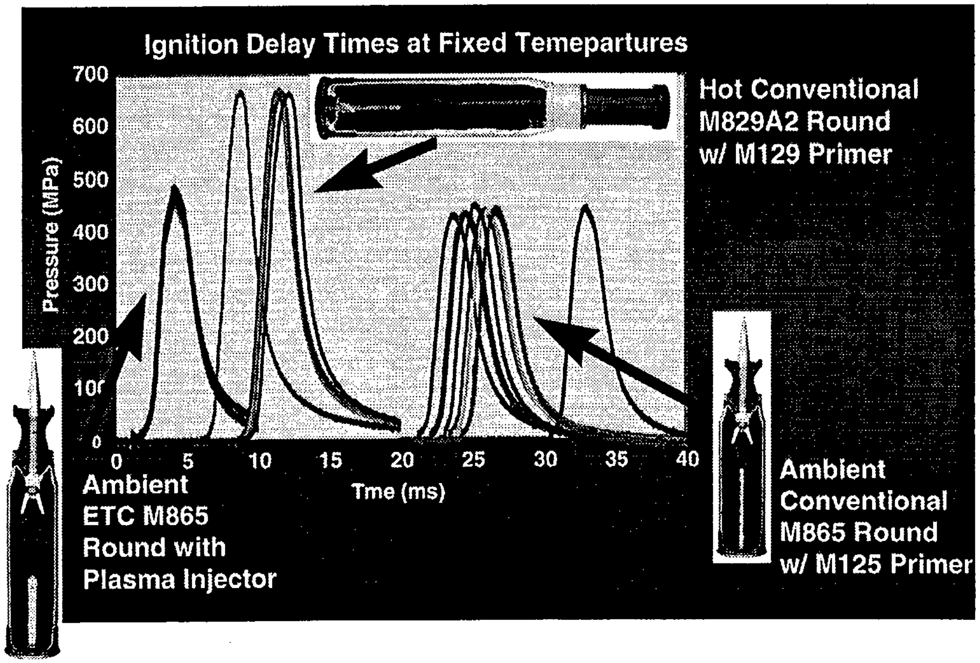
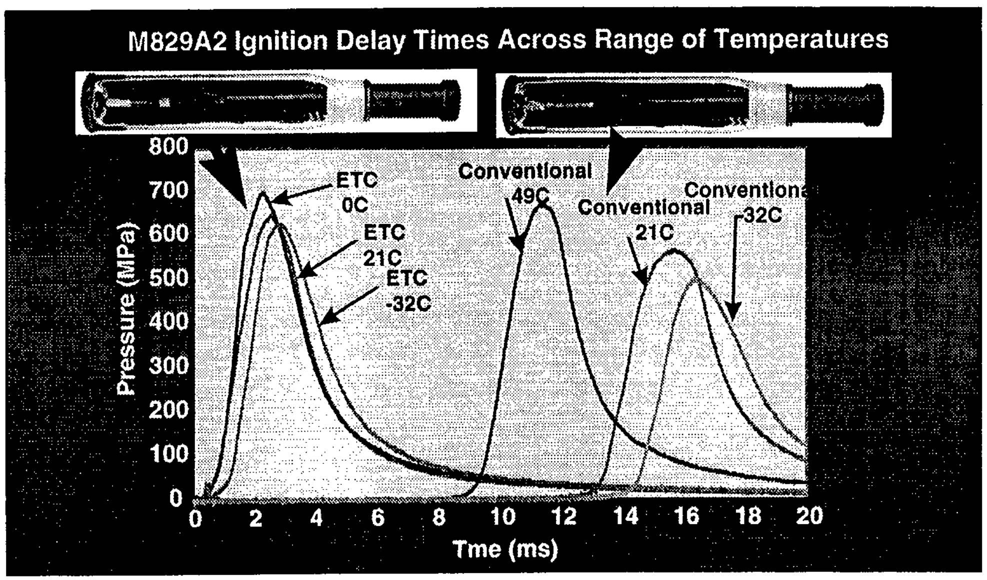
EEF Follow-on Program





ETC Ignition Provides Significant Reduction in Temperature Dependent Ignition Delay and Variation Over Full Temperature Range

Probability of hit from a moving tank approaches the probability of hit from a stationary tank.

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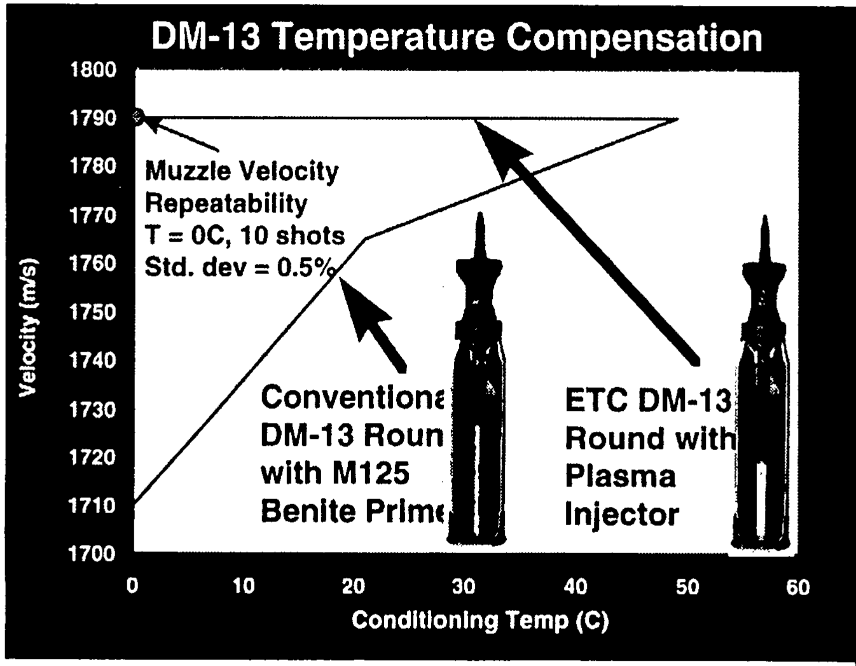
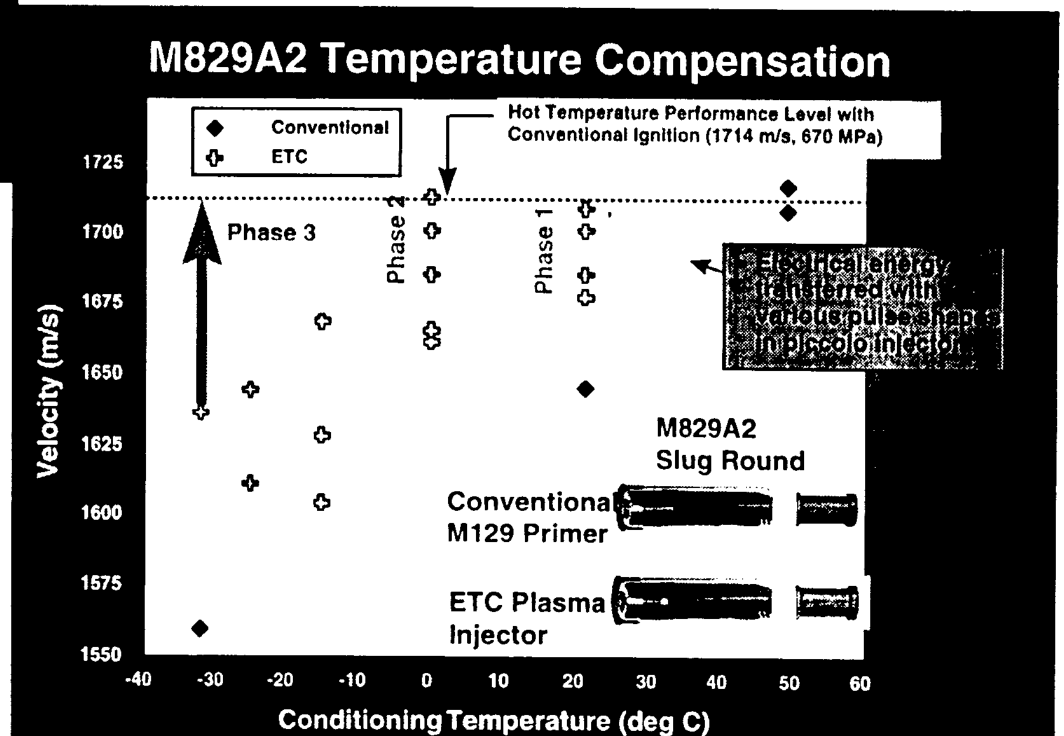
EEF Follow-on - Summary





- *The Lethality of an ETC Cannon is Constant Across Temperature*
- *An ETC Equipped M256 Cannon Will Provide Substantial Lethality Improvement to Currently Fielded Ammunition*

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A German-U.S. workshop, under the auspices of DEA-G-1060, focusing on electrothermal-chemical (ETC) gun propulsion was held at the U.S. Army Research Laboratory, Weapons and Materials Research Directorate, Aberdeen Proving Ground, MD, on 27–28 January 1998. The workshop was attended by approximately 60 researchers from Germany and the United States. Eighteen invited talks covering the areas of ETC Program Overviews, Pulsed Power, Modeling and Simulation, ETC Systems, and Plasma Propellant Interaction were presented during the two days.

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